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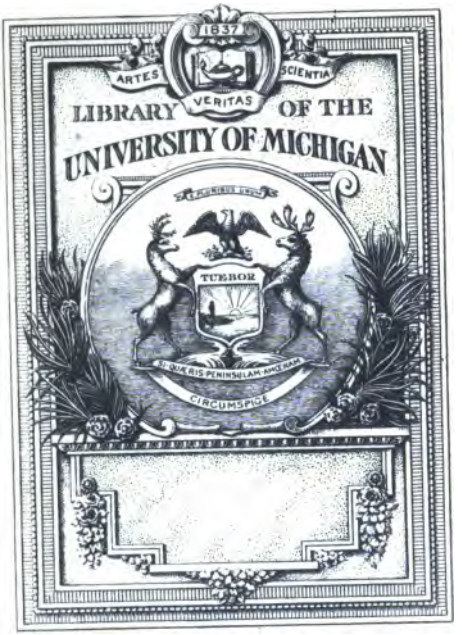
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# WITHIN THE ATOM

## A POPULAR VIEW OF ELECTRONS AND QUANTA

BY

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# PREFACE

THIS volume is intended for readers who wish to obtain a familiarity with the basis of modern physical science. Without mathematical formulation it deals with modern theories as to matter and energy, emphasizing the granular structure and electrical nature of matter, and the apparently corpuscular character of energy.

The reader need have no previous knowledge of electricity, mechanics, or chemistry. For the appreciation of the evidence of certain critical experiments upon which modern scientists base their belief in electrons and in quanta of energy some knowledge of electricity, however, is required. To supply this in a quick and easy manner, the usual historical order of presentation is abandoned and the correctness of modern theories is assumed at the start. There are postulated the electron and its counterpart, the proton. In terms of these there are then described those few phenomena of electricity which are essential to the later consideration of the evidence. In this way, it is hoped most rapidly to introduce the reader to modern theories as to the invisible workings of the physical universe.

J. M.

WYOMING, N. J.
June, 1921.



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# INTRODUCTION

In the constellation of Orion is the bright reddish star Betelgeuse. For centuries it served with other stars as a guide to mariners and as an object for consideration by philosophers and myth makers. Although we still retain the name given to it by the Arabs and still see it as the right shoulder of the mighty hunter, science has removed all but the nomenclature of the earlier animistic interpretation and substituted cold quantitative facts. Since our school days we have known that Betelgeuse is a sun, essentially like that which illuminates our earth. Very recently we have been told by Professor Michelson of Chicago as to its astounding magnitude—three hundred times the diameter of our own sun. The methods by which he arrived at this relationship involve interesting theories and required precise experimentation. Like the newspapers, however, of the day following his announcement let us be content for the moment with the fact itself.

In the midst of the universe in which Betelgeuse is but a speck exists a smaller sun on a planet of which there crawl what Bertrand Russell aptly called tiny lumps of impure carbons and water. What a shock to the ego-centricity of these carbon compounds to realize their quantitative insignificance in comparison with Betelgeuse.

About this larger sun there are probably encircling planets. Are there organic compounds on any of these and how do they arise from inorganic compounds as the ageing planet slowly cools? Are there conditions of temperature and atmospheric content which are accompanied by such chemical changes? If organic substances can be formed will life appear on the planet? What intimations of the evolution of life can be found in modern science?

Our questions grow by association, overlapping one another, repeating and varying their content; and our apparently unbound speculation leads only to further questions. Some answers and much material for thought are vouched by modern science although the specific question as to the mechanism and process in the evolution of life remains unanswered.

What in fact do we mean by life? The caterpillar in its cocoon awaits the proper temperature for its metamorphosis: the radioactive atom spontaneously emits an electron and becomes a new substance. Both caterpillar and radioactive atom are but stages in a sequence of events, the one to be followed by more caterpillars all of which will differ slightly from the original and the other by more atoms which will differ radically from the original. The comparison is not too seriously intended although it is safe to say that the offspring of the radium atom will be moving in fast circles ages after the descendants of the moth have perished from the face of the earth.

When we have reached a satisfactory definition

of life shall death be its negative? Are life and death merely convenient terms which we loosely apply to phases in a wide process of continuous change? and what are the entities which are conserved during the change? To the last question science today may apparently give answer for in energy and in electricity it has two entities which are conserved in amount. The former manifests itself by changes in the location of the latter, for electricity is the only known constituent of the ponderable matter of which our universe is composed.

Whether we are interested in speculative questions like those just mentioned, in less speculative but yet unsolved questions like the mechanism for the transmission of stimuli by nerves, or in the purely practical matter of the efficient organization and operation of the multiplicity of machines which condition our daily lives, we must seek explanations in terms of energy and electricity.

The reduction of the number of unknowns with which science deals is a recent advance which has followed discoveries like those of radium and X-rays. Widely different branches of science are now known to be dealing with the same fundamentals of electricity and energy. For the first time in centuries there exists the material which a genius could synthesize into a universal science, in which physics and chemistry, biology and geology, will lose their identities in a common set of principles.

So rapid, however, has been the advance of science toward this simplification of terms and prin-

ciples that few except those immediately concerned are aware of the possibilities. With the change of base and point of view which has followed the discovery of the electron, and the consequent interrelation of branches of science long held apart, there have arisen innumerable questions which occupy the time of those best able to expound the new science. Our schools follow but tardily in their elementary classes the conclusions of researchers in science and our text-book writers must comply with existing distinctions between branches of science.

The fundamental concepts of the new science are easy to grasp and may be stated in relatively simple terms, although the quantitative relationships are to be expressed only in mathematical symbols. The complete synthesis may be upon us some day as unexpectedly as were Einstein's hypotheses and presumably to find us as unprepared. For its critical consideration but few will be competent. For a more popular appraisal many of us may be prepared if we have learned to think of all scientific problems in terms of electricity and energy.

Unfortunately the popularizer of these concepts must run some risk of false statement for he is limited first by his own knowledge and interpretation of the accepted body of scientific truth, and second by the necessity of purely verbal expression. Word pictures are all that he may give and the selection and emphasis of their material may carry implications which time shall disprove.

One difficulty which confronts those who would impart the concepts, evidence, and conclusions of

modern science to readers untrained or impatient of mathematical formulation, arises from a weakness which is characteristic of modern research itself. Science today is quantitative rather than qualitative. It expresses the relationship of the intensities of two phenomena, as for example the intensities of the electric current and of the illumination of an incandescent lamp, and compensates for its inability to answer the question "how" by its wealth of data as to "how much." Research monograph and text-book alike emphasize the observable quantitative relationship and rarely venture far into the speculative hinterland where "how" must precede "how much." As we teach science today in our schools the effort of learning the quantitative relationships too frequently leaves neither the instructor nor the student leisure for fruitful inquiry or speculation as to the mechanism itself.

Rare indeed is the Faraday whose pictures of invisible processes satisfy and vivify quantitative relationships during a century of fruitful research. That particular genius was discovered by Sir Humphrey Davy, himself a broad and versatile mind. One wonders whether our phonographic classroom methods and the machine processes of our laboratory instruction can create an environment for that inspiration of another Faraday which the present development seems to require.

Faraday's pictures were in the nature of working hypotheses as to an all-embracing and continuous medium—an elastic ethereal medium. Assuming that an ether existed, the attraction or repulsion of

electrified bodies was explainable, in terms of the strains which the bodies introduced into the medium, without recourse to a theory for action at a distance.

During the later half of the 19th century, the assumed medium became of first importance and scientifically electricity was in danger of becoming a phenomenon of the very medium which had been assumed to explain its own phenomena. The emphasis on the medium, however, had happy results for it led Maxwell to the conclusion that light was an electro-magnetic phenomenon.

With the discovery of the electron—the apparently indivisible particle of electricity—the ether rapidly lost its importance and finally with the work of Einstein it has ceased to be a necessary postulate in physical science.

The terminology of the older physics of the ether is unavoidable, however, if one approaches the new physics of electrons in the historical order of its evolution. Such a method of presentation has the advantage that the experimental evidence may be set forth in conjunction with each statement of fact. On the other hand, the method demands on the part of the reader a knowledge of the phenomena and laws of electricity, mechanics, and chemistry which is seldom possessed by the hypothetical person "the general reader." This deficiency may, of course, be supplied by devoting to that purpose the earlier chapters of an exposition, but several of these would raise memories of high school textbooks. The facts which must be acquired would

of necessity be presented in a conventional manner. It would, therefore, be necessary to return to them, after treating the fundamentals of the new science, and attempt a corrective interpretation in the new terms. The process would not only be wasteful of time but difficult of attainment for first impressions, even of science, lie deep in the mind.

It is perhaps better to start out boldly, stating the physical basis of the new science and building as far as practical on its firm foundation. For certain portions of the superstructure only sketches are available, and for others not even such indications. Occasionally there may be sketches of several draftsmen neither of whom seems destined to be accepted as the final designer. Enough material, however, may be inspected by the reader so that he may appreciate the problem of the new science and the point of view. Only when the structure is partially completed should the reader be expected to recognize its relation to the science of his own school days, for the new science starts with the invisible and intangible entity of electricity.

# WITHIN THE ATOM

## CHAPTER I

### ATOMIC STRUCTURES

THE story is told of the débutante who met the renowned astronomer, the lion of the evening, with an appreciative remark as to the wonders of astronomy, "And do you know I think the most wonderful thing is how we know the names of the stars."

Now imagine, if you can, two types of particles, each invisible, intangible and infinitesimal in the ordinary senses of these words, and indeterminate in form and substance. For one type, wonderfully enough, we know the name "electron," but for the other type there is no agreement. We are free to choose from a number advanced by various scientists and shall arbitrarily adopt the term "proton."

Electron and proton are complementary. Together they may merge in a union so close that their combined size is less than that of the electron alone. Such a statement may sound absurd but experiments seem to indicate that the union of two or more protons with one or more electrons is a smaller particle than is a single isolated electron. The form

and size of the electron and proton must then be different in combination from that of the free electron and free proton respectively.

We apprehend at the start two types of particles both invisible but both independently observable by certain effects which they produce. To these we ascribe complementary properties. In so doing we meet at once a serious difficulty of existing language for there is a paucity of terms by which we may describe the particles without connotations of an animistic bias. The protons and electrons are complementary, mutually supplying each other's needs. Electrons, however, are mutually antagonistic and depart from each other's presence unless restrained. The same is true of protons. It is only by virtue of the complementary properties of proton and electron that two or more electrons, for example, are constrained to the same infinitesimal space.

A close union of a group of protons and electrons is conceivable from a social parallel for it may resemble geometrically the careful seating of guests at a large dinner. Between those of opposing interests might be placed others whose interests are mutual with those of their immediate neighbors. The dinner guests have various degrees of sympathy and antipathy for each other. Between electrons, however, there is but one degree of antagonism since all experiments point to the exact similarity of all electrons without regard to their individual histories. The same apparently is true of protons although the isolation of the latter has been a more recent advance and there is not as

large a volume of evidence in this case. We are probably entirely safe in assuming that protons are indistinguishable and are interchangeable to an extent that would excite the admiration of the piece-part manufacturer of the present days of quantity production.

Any grouping of antagonistic elements, for example, electrons, can persist only by virtue of the presence of the complementary type, in this case protons, and by virtue of such geometrical arrangement that the opposing tendencies of the elements of the same type are neutralized by the complementary tendencies of elements of a different type and in part by tendencies which are discussed on page 76. According to some theories, however, two electrons or two protons are pictured as mutually attracted when they are very close together, although at larger separations they are repellent. Similarly an electron and a proton would start to repel each other after they had approached to within a certain small distance of each other. In any case the permanence of a group of protons and electrons will depend upon the geometrical arrangement. The picture which we may form is like that of some state of society where man shuns man, and woman avoids woman, but unrestricted promiscuity prevails. Promiscuity, however, carries no stigma for individuality is entirely lacking.

In many ways their society approaches an angelic state, for its members are not confined to a terrestrial plane but hover and flit about in space, subject to the opposing tendencies which were just men-

tioned. Nor are their antagonisms destructive like those of humans, despite the fact that electrons may rush about with a speed almost that of light. Actual collisions between like elements are always avoided by swerving to one side or in the extreme instances of head-on approach by retracing their paths. A deathless existence these particles lead and although there is marriage and giving in marriage the unions are fruitless. The number of electrons or of protons in our universe is believed to be eternally fixed so that their immortal society may alter only in its configurations.

Such new configurations as these elements may assume are formed under the action and in conformity with the laws stated figuratively above. In more classical terms these may be expressed by saying that like elements repel and unlike attract. To place this idea completely beyond the animistic bias two words of recent coinage and incompletely sanctioned usage may be employed. Electrons pellate, protons pellate, but an electron and a proton tractate.

The law reminds one of that for the action of electrical charges, since like charges repel and unlike attract. It may be admitted at once that electrons are elements of so-called negative electricity and protons elements of positive electricity. It is preferable, however, to consider further this question of configuration of these elements before attempting to relate our present treatment with the familiar facts of electricity. We shall nevertheless

find it most convenient to speak of electrons and protons as the "electrical elements."

The electrical elements are found associated in configurations which increase rapidly in complexity as we pass from the simple union of one proton and one electron to systems which involve hundreds or thousands of elements. When more than one proton is involved two types of systems are possible. In the simpler type all the protons are associated in a compact group which comprizes also sufficient electrons to secure a certain degree of stability for the coalition. Such other electrons as may be associated with the system under consideration are external to the compact group or *nucleus* as we shall call it. This simpler type of system we shall call atomic, and to the question of its stability we shall return later.

The second type of system is that which involves two or more nuclei and associated external electrons. Again we postpone the question of degree of stability and class such systems as molecular.

For completeness we should mention at this point also systems which may be formed by combinations of the two main types. A number of similar systems, for example, molecular systems, may become closely associated by a temporary relinquishment of individual freedom and form a federation, to borrow a term which closely fits. As long as the external conditions remain as they were this federation may persist but its component members may on occasion and without prejudice assume again

their individual existences. Polymeric systems of this kind are of frequent occurrence.

As the opposite of polymerization there is dissociation, the process of separating a polymeric or even a molecular system into the smaller systems which compose it. With the latter process particularly we shall have more to do later.

For the moment, however, we shall consider only the simplest type of system, namely the atomic, which is formed by a nucleus and a number of electrons external to it. In the nucleus there are always more protons than electrons. It is this excess of protons that serves by virtue of their inherent complementary characteristics to retain in the region immediately external to the nucleus a number of electrons.

Consideration will be further limited by excluding for the present all systems in which the total number of electrons, including those external to the nucleus as well as those comprized by it, is unequal to the number of protons in the nucleus. Systems in which there is numerical equality between protons and electrons we shall call normal atoms or, more conventionally, uncharged atoms. We shall further find it convenient to classify such atomic systems by the number of electrons external to the nucleus, or what amounts to the same thing by the excess of protons in the nucleus. This number will be designated the "atomic number."

The largest known atomic number is 92 and this corresponds to the chemical element uranium, a metallic element found in pitchblende. It was in

residues of this mineral, from which the uranium had been extracted, that Professor and Mme. Curie discovered the element radium. Radium has an atomic number of 88. Another chemical element, which has a large atomic number, is thorium, a rare metal used in making incandescent gas mantles. Its atomic number is 90.

Atomic systems with such high atomic numbers are very rare in the collector's sense of the word. Let us imagine a period long past in the history of our universe when such systems predominated even to the exclusion of systems of smaller atomic numbers. Their nuclei were crowded spaces filled with antagonistic electrical elements—insecure coalitions ready if necessary to sacrifice some of their members. Whether under external influence or solely from internal causes these coalitions started to expel their members. The electrons left as individuals, ejected with enormous velocity, or in company with protons with smaller velocities as befitted a larger party. Such a party was apparently composed of four protons and two electrons, and to it we give the name "alpha particle."

Under some conditions the reduced coalition would be left so unstable by such action that a further expulsion would be necessary in the next few seconds. Sometimes days would elapse and under other conditions years or even ages might pass before such violent readjustments again took place.

Today we may observe the same process in the case of atomic groups of high atomic numbers—

the so-called radioactive elements. The changes in nuclear composition appear in the case of these elements to be independent of external conditions and to occur solely because of the need of readjustment on the part of the elements of the nuclear coalition.

By a sequence of expulsions of electrons and of alpha particles the highly complex nuclei of the prehistoric atomic systems were reduced in number of electrical elements and increased in stability until finally the apparently stable atomic structures of our ordinary chemical elements were attained. In other words, we may consider the chemical elements like tin, lead, sulphur and oxygen to be "end-products" of a long series of radioactive changes. The character of these changes and the alterations in the properties of the atomic systems which result will be discussed in considerable detail in later chapters.

Although the disruption of the complex nuclear structure of a radioactive atom is spontaneous in the sense of occurring without the stimulus of external agents, similar disturbances do not occur simultaneously in all the individual atoms of a large group. Some of the atoms of a bit of uranium, for example, or of radium, are always breaking down. The product of the disintegration may be removed by trained experimenters and hence the rate at which it is formed may be measured. Knowing the rate at which disintegration is occurring, it is a matter of simple mathematics to calculate the average life, that is the time required until half

the original atomic systems will have disintegrated. This is using the term "average life" as actuaries do, for of course some of the atoms may last for ages without dissociating.

In the case of radium the average life is estimated as about 1600 years; that is, it should require that time for half the atoms of any bit of radium to become changed into atomic systems of smaller numbers of elements. Curiously enough the next atomic system, a gaseous element known as "niton," has a short average life of only five or six days. The atomic number of niton is 86, for it is the result of the ejection of an alpha particle from the nucleus of the radium system, which has an excess of 88 protons.

The alpha particle is itself an atomic system, although it is not a normal or uncharged atom since it involves more protons than electrons. If two external electrons are associated with it, it becomes a normal atom, namely that of helium, a light inactive gaseous element which has recently attracted public attention as a desirable substitute in filling balloons for the lighter but active element hydrogen which burns with oxygen.

It was perhaps by such spontaneous changes in the composition of the nuclei of atomic systems, as are illustrated today by radium, that the known chemical elements were produced. The definition, however, of the term "chemical element" is no longer as simple as it was in the days before this disintegration theory was advanced and accepted by scientists. Until we have discussed with further

detail the possible changes which may occur in atomic systems, we may use the term in its usual sense, and say that the eighty, or so, known chemical elements are the products of radioactive disintegration for which the further disintegration is so slow as to be negligible or inappreciable.

For present purposes we may assume that our chemical elements are end-products of prehistoric disintegration, leaving aside the question of a previous over-enthusiastic integration. Some evidence of the building-up of atoms is arising in the study of the spectra of stars. In a few years these integration processes may be as well understood as their radioactive reversals are today.

# CHAPTER II

## SATISFIED AND UNSATISFIED SYSTEMS

It is difficult to describe the interactions of the electrical elements without recourse to words which have an emotional significance. Words like stable and unstable, or active and inert, might be used but they have scientific connotations which are better avoided at present. In continuing the discussion of atomic systems we shall use words which are frankly animistic and classify these systems as satisfied, unsatisfied, or dissatisfied. The radioactive systems which were described in the previous chapter are evidently violently dissatisfied systems.

A failure of satisfaction may be the result of a deficiency in the quantity or in the quality of the desired good. Quantitatively an electrical system is satisfied if there is an equality in the number of protons and electrons which comprise it. Satisfaction as to quality, on the other hand, depends upon the configuration of the component elements of the system.

Dissatisfaction when it occurs is deep seated—a neurotic condition of the nucleus which may result without any external stimulus in violent outbursts and a veritable orgy of smashing china and throwing things about. This excitable state is

characteristic of those atomic systems which have retained their youth and been unchanged by the years. When they shall have become as lead, a long peaceful life will confront them, in which they may be at times unsatisfied but practically never dissatisfied. During the formative years of their discontent the nature of their dissatisfaction adapts itself to their condition, being now concerned with quantity and again with quality or configuration. At times they throw off alpha particles and thus find themselves with an excess of electrons which are a source of dissatisfaction in their innermost and nuclear hearts. The electron which is then expelled from the nucleus is sometimes spoken of as a beta particle. By expulsions of alpha and beta particles the radioactive systems lose much of their energy and all appearances of radicalism.

For a time, however, we shall deal with the conservative atoms which never become more than mildly unsatisfied. Systems which are unsatisfied in the numerical equivalence of protons and electrons show the effect of electrical charges. The consideration of these effects also must be postponed and our attention fixed upon systems which are satisfied in this quantitative relationship but are unsatisfied in the configuration of their component elements. Such absence of satisfaction as then exists is solely a matter of the arrangement of the electrons external to the nucleus since, if the source of the trouble were in the latter, dissatisfaction would be manifest unmistakably.

The electrons which are external to the nucleus

of an atom are separated from it and from each other by relatively large distances. Perhaps as good a picture of an atomic system as may be easily formed is obtained by a comparison with our solar system. The distances between sun and planets and between the various planets are very large as compared to the diameters of any of the planetary bodies. If we now imagine the sun to be very small as compared to the earth and then imagine all the distances and sizes to be proportionally reduced until the system is invisible even with the most powerful microscope we have a possible picture of an atomic system. The sun is first made smaller because the nucleus is small compared to the electron. Some dimensions of such a system are quite accurately known for they are determinable by methods which will be described later.

The diameter of the atom depends upon its construction, being smaller for some chemical elements than for others. If we wished, for example, to keep out of the way of a hammer thrower, starting his turns, we would assume that his diameter was that of the circle through which the hammer head swung. In much the same way the diameter of any atom is that of the circle of which the center is the nucleus and the radius the distance to the outermost electron.

The hydrogen atom is composed of only one proton and one electron. The two elements are probably whirling about each other in space much like a rapidly whirling dumbbell except that there is no direct connection between the ends of the

dumbbell. The atomic diameter is about two hundredths of a millionth of a centimeter, but this is about one hundred times as large as that of the electron. The diameter of an electron is about two tenths of a thousandth of a millionth of a centimeter, as the most recent investigations indicate.

The other atoms are not so simple. The helium atom, of which we have spoken before, consists of a nucleus and two external electrons. The atom of sodium has eleven, and that of chlorine seventeen electrons, external to the nucleus. We do not know as much about the arrangement of the electrons in the atomic structures as we should like or as we probably shall in the near future. For the purpose of discussing the effects of the configuration of the external electrons we may, however, draw one or two parallels of a kindergarten nature which will serve in default of more authoritative pictures.

The system of nucleus and external electrons may be likened to a few children playing a circle game about a teacher. Suppose that the game goes best with eight in the ring but is possible with any number between six and ten. If ten are playing, that is if the teacher's responsibility is for ten, as might be the case for electrons if the nucleus has ten excess protons, then there is some crowding. An opportunity for two children to join an adjacent but less crowded circle will be welcomed by the children, and by the teacher also, if she can satisfy her quantitative obligations by supervising their play in a neighboring circle.

An atom with a circle crowded by electrons is in

an unsatisfied condition which is favorable to losing electrons. If it does so it will have more protons than electrons. This tendency towards an excess of protons is ordinarily described by calling the atom electropositive. It can supply electrons to any other atom which can accommodate them in its circle. If it does so, however, the two atoms must remain together for each nucleus has responsibility for a definite number of the total of electrons. For such a combination into a molecule the second kind of atom must have a complementary need, having fewer electrons than can be satisfactorily accommodated in its ring. Its tendency to acquire added electrons is indicated by calling it electronegative.

If an atom has a ring of electrons just sufficient to play their circle game without crowding there will be no need for loaning or borrowing from an adjacent atom, and hence no occasion for combination into a molecule. The elements with atoms of this character are "inert" substances such as the gases helium, argon, neon and krypton. Niton is also an example of such an arrangement. Niton, however, is inert only as far as concerns its possibility of combination with other atoms, for, due to its radioactive properties, it can very markedly influence the chemical behaviour of other substances.

So far as concerns the combination into molecular systems of two different kinds of atomic systems, we should expect electropositive atoms to unite with electronegative ones. Common salt, NaCl, is the combination of the electropositive sodium atom, which would spare one electron, with the electroneg-

ative chlorine atom, which would accommodate an extra electron. In forming the molecule the electrons probably redistribute themselves about the two nuclei.

Under certain conditions the combination so formed may be broken up into two new systems, which are slightly different from the original sodium and chlorine atoms. If salt is dissolved in water some of its molecules separate into these two parts. One has the nucleus of a sodium atom and the other that of a chlorine atom. The number of electrons about each of these nuclei is not that of the normal atom. In the process of separating, the electron which was borrowed by the ring about the chlorine nucleus is not returned.

The chlorine nucleus and its ring with an excess electron is not a chlorine atom, nor is the sodium nucleus with its ring, which has lost an electron, an atom of sodium. When ordinary table salt breaks up in solution, it does not give the elementary substances of sodium and chlorine, neither of which is a possible food. These new atomic systems move about in the solution exactly as do unsplit molecules. To them is given a new name, that of "ions" since they are go-ers. Sometimes they come together in their wanderings and for a time form again a salt molecule but later they may break apart.

The phenomena of solution and in fact all matters having to do with the motions through space of atomic or molecular systems must be postponed. The dissociation of the molecular system of sodium chloride into atomic systems has been cited as a step

toward the fuller study of the combination of atomic systems into molecular systems. When the sodium ion, that is the positive ion, comes into the immediate neighborhood of the chlorine, that is the negative ion, recombination will again occur although a dissociation may immediately follow as the result of those external influences which we are at present assuming without explaining.

Ions are atomic systems unsatisfied in quantity rather than in configuration of electrical elements. Combination of atomic systems into molecular systems is, therefore, seen to occur as the result of either type of unsatisfaction. For historical reasons both of the kinds of combination, which we have pictured above, are called chemical combinations without regard to our more recent knowledge that they are entirely electrical phenomena.

The ability of an electropositive atom, for example sodium, or of a negative ion, for example the chlorine ion, to enter into a molecular combination depends (as we have seen) upon the possession of one (or more) electrons in excess of those requisite to satisfaction in configuration or in quantity, respectively. We may therefore express the ability of an atomic system to combine, which is conventionally termed its valence, in terms of the number of electrons which measure its unsatisfaction. Thus we may say that the atomic systems mentioned immediately above have a positive valence of one. The atoms or ions which become the partners in such combinations have a complementary need of elec-

trons. They may be described as having a negative valence of one.

For a satisfied system, that is for an inert atom, the valence is, of course, zero.

The satisfaction of that need on the part of an atomic system which is expressed quantitatively by its valence may be obtained in a number of ways. A monovalent atomic system like sodium requires only another monovalent system, like chlorine, which has a complementary need to form a satisfied molecular structure. A divalent atom, on the other hand, may be satisfied by a union with another divalent atom or with two monovalent atoms. In the latter case the two necessary atoms may be of the same kind or different. In the molecular system of water the divalent oxygen atom is combined with two similar monovalent hydrogen atoms. The symbol $H_2O$, in which the subscript indicates the number of atoms of the type to which it is affixed, is a convenient representation of this combination. In similar manner the molecular system formed by the divalent oxygen atom with two unlike atoms of sodium and hydrogen is symbolized as NaOH.

Many atomic structures attain satisfaction by combining into molecular form with others of their own type. Thus hydrogen normally exists in a diatomic molecular state represented as $H_2$. The same is true of oxygen which forms a molecular system of $O_2$. In such cases we find a combination of two atomic systems with similar rather than complementary needs. The rearrangement of the electrons about the two nuclei, apparently, results in a more

stable configuration than exists in the individual atomic structures although sometimes not as stable as it might be. A spark will explode a mixture of hydrogen and oxygen and result in two molecules of water being formed from one molecule of oxygen and two molecules of hydrogen. The operation is conveniently symbolized as $O_2 + 2H_2 \rightarrow 2H_2O$.

The atomic system of oxygen is the great joiner and has fraternal relations with all except the most deadly dull and inert atoms.[1] It belongs to thousands of complex molecular societies. Associated with hydrogen it enters as water of crystallization into secret organizations of molecules of which it is not a bona fide member but from which it may be expelled only by heated action. Even then all the water molecules do not leave with equal readiness for some resist expulsion with considerable tenacity.

It was largely by a study of combinations of oxygen with nitrogen that Dalton arrived at his well known laws as to molecular composition. The substance of these laws has been tacitly assumed in our earlier discussion. The unit in chemical combinations is the atomic system; and molecular systems are formed only from whole numbers of atomic systems.

[1] And fluorine.

# CHAPTER III

## THE PERIODIC TABLE OF ATOMIC SYSTEMS

An atomic system is formed by a nucleus and a number of electrons external to it. In the configuration of these external electrons is to be found the secret of the ability of one atomic system to combine with one or more other systems to form a molecular system. The valence, which measures this ability to combine, may be positive or negative depending upon whether the system under consideration is unsatisfied as the result of too many or of too few electrons for a stable configuration of the external electrons.

In the nucleus there is always an excess of protons and the number by which this excess is specified is known as the atomic number. The largest known atomic number is 92. On the basis of atomic numbers, therefore, a classification may be established of 92 types of atomic systems. These types may then be cross-classified on the basis of valence.

As we proceed from one type of atomic system to that with the next atomic number there is a change of one in the number of excess protons in the nucleus and a corresponding change of one in the number of external electrons. For example, let us enter our system of classification by atomic numbers

at the eleventh type, which is that of the sodium atom. We must picture this atomic system with eleven excess protons in the nucleus and eleven external electrons, the actual configuration of which is still problematical. Despite the fact that there is a quantitative balance between the protons and the electrons, of complementary properties, there is a lack of satisfaction in the portion of the system comprised by the external electrons.

In the system of next smaller number there are ten external electrons; and with the reduction in number the unsatisfaction has disappeared, for the tenth typical system is that of neon, an inert atom. The equivalence of number of protons and electrons still remains for both kinds of electrical elements have undergone the same reduction in number. The external electrons, however, no longer crowd each other.

What would one naturally expect as the atomic number is further reduced? Eleven electrons crowd, ten do not, but nine are too few for satisfaction of the requirement of stability. The atomic system of the ninth type, known as fluorine, despite its quantitative satisfaction, is unsatisfied in configuration by one electron. Like the sodium system it also has a valence of unity but negative instead of positive.

The satisfied atomic system is thus seen to occur as a transition between systems of negative and positive valence. Such transitions occur at the atomic systems of helium, neon, argon, krypton, xenon, and niton for which the atomic numbers are respectively,

2, 10, 18, 36, 54 and 86. For convenience the names of the various types of systems corresponding to the atomic numbers below 22 are given in the accompanying table.

TABLE I

THE NAMES AND NUMBERS OF THE ATOMIC SYSTEMS

| | | | | | |
|---|---|---|---|---|---|
| 1 | Hydrogen | H | 12 | Magnesium | Mg |
| 2 | Helium * | He | 13 | Aluminum | Al |
| 3 | Lithium | Li | 14 | Silicon | Si |
| 4 | Beryllium | Be | 15 | Phosphorus | P |
| 5 | Boron | B | 16 | Sulphur | S |
| 6 | Carbon | C | 17 | Chlorine | Cl |
| 7 | Nitrogen | N | 18 | Argon * | A |
| 8 | Oxygen | O | 19 | Potassium | K |
| 9 | Fluorine | F | 20 | Calcium | Ca |
| 10 | Neon * | Ne | 21 | Scandium | Sc |
| 11 | Sodium | Na | 22 | Titanium | Ti |

* Transition system

The atomic system for which the atomic number is one less than that of a transition system has a negative valence of one, and the system of the next greater number has a positive valence of one as in the case just mentioned of the sequence fluorine, neon, and sodium. Progressing toward higher numbers the positive valence increases, and toward lower atomic numbers the negative valence. In progressing from one satisfied system to the next as, for example, from neon to argon, there must therefore be another kind of transition from negative valence to positive. Between these satisfied systems there are three types with positive valence of one, two and three, respectively, namely, sodium, magnesium, and aluminium, and three types, namely, chlorine, sulphur and phosphorus, with the corresponding values of negative valence.

The middle system of the sequence, which we are considering, is like a hostess who is planning a dinner. Shall she invite four more guests or four less? The decision will depend upon circumstances, that is upon who the guests are to be, but the number she will add or scratch from her list is preferably four, since that will make a satisfactory grouping. Sometimes she makes one choice and again the opposite choice and the same is true of the atomic system of silicon. Its valence is four but it is amphoteric for it partakes of the character of both electropositive and electronegative elements.

The simile of the hostess, however, is inadequate, because the electrons are disposed about the nucleus in a space of three dimensions. The pictures of their disposition, which have been proposed from time to time, are all incomplete and none has been generally accepted by scientists. The successful picture must account for the known facts of chemistry and also for those facts of physics which relate to the radiation of light from atomic structures. The maximum number of electrons which may be concerned in atomic phenomena is, of course, definitely known since the atomic numbers are well substantiated facts. The grouping of these electrons, however, is still in the stage of hypothesis and the picture which will now be given is merely that which today most satisfactorily accounts for the largest number of the known phenomena.

We imagine [1] that the electrons are disposed about the nucleus as if they lay in the shells of one of those

[1] According to G. N. Lewis and Langmuir.

Chinese toys which consists of a concentric series of wooden egg-shaped shells. Let the innermost egg represent the nucleus. In the next or first shell there may be one or two electrons, one in the case of hydrogen and two in that of helium. The latter condition would obviously admit of a stable structure in which electrons on diametrically opposite sides of the nucleus were held in the system, because they tractate with this nucleus, despite the fact that they pellate with each other. Because of this electrical stability, the atomic system of helium is inert.

Except for the hydrogen system all atomic structures have these two electrons. The unsymmetrical configuration of the hydrogen system accounts for its extreme activity as a chemical element, and also for its formation of diatomic molecules of hydrogen gas.

When an atomic system contains more than two external electrons, all electrons in excess of two are disposed on shells external to that which was just described. The next outer shell is believed to be twice as far from the nucleus, and hence to have four times the superficial area. In it a total of eight electrons may be located.

The atomic system which has one electron in this second shell is that of lithium. This atom readily parts with its third electron and assumes the more stable configuration of the helium atom. That is what takes place when the molecular system of lithium chloride, LiCl, dissociates into a lithium ion and a chlorine ion. Geometrically a lithium ion is similar to the stable helium atom, but it does not act at all similarly because the nucleus of lithium

has three excess protons instead of the two of helium.

With two electrons in the second shell the atomic system is that of beryllium which has a positive valence of two since it takes the loss of two electrons to convert it into the stable configuration of the helium system. Boron is a system with three electrons in this shell. When the number is four, there is reached the important system of carbon which enters into all organic compounds. Its four external electrons in pellating with each other probably take places such as to form the corners of a solid figure of four equal sides. Nitrogen has five, oxygen six, fluorine seven, and neon eight electrons in this second layer. In the last case the electrons will distribute themselves four on each hemisphere, so that they form the corners of a cube at the center of which is the inner shell with its two electrons and within this the nucleus. The inertness of the neon atom is well accounted for by this symmetrical and stable arrangement of external electrons.

The system of fluorine with its seven electrons in the second shell may be considered either as having seven too many for such stability as is possessed by the helium system, or one too few for the stability of the neon system. In other words, it has either a positive valence of seven or a negative valence of one. Oxygen has six and two respectively. The rearrangement which is required to make these systems stable, that is satisfied in configuration, is less if electrons are added than if they are subtracted, so that such systems tend in combination to attain their satisfaction by borrowing from the other com-

ponents of the molecular systems in which they are associated.

In the dissociation of such molecular systems the atom tends to retain its satisfaction by a failure to return the borrowed electron which amounts to an actual theft. Dissociation, therefore, results in the formation of negative ions, that is those with a quantitative excess of electrons.

In a large number of cases of molecular systems the electrons are shared so that borrowing and theft do not occur. It seems probable, however, that individual electrons may not be shared but only pairs of electrons.[1] It is further believed that in the sharing of pairs of electrons the adjacent atomic groups so combine as to form as nearly as possible stable arrangements roughly similar to that of the neon atom, that is groups of electrons at the eight corners of a cube, at the center of which is a kernel composed of two electrons and a nucleus. This hypothetical process is peculiarly adapted to explain, for example, the large number of compounds which are formed by oxygen with nitrogen.

As the number of external electrons is increased beyond ten a new outer shell is required. Let us picture this third shell as practically coincident with the second. The first electron to be disposed in it occupies a position with much the same precarious-

[1] Chlorine, which forms a diatomic molecule, $Cl_2$, is a good illustration of the sharing of electrons between the atoms of molecular systems. Each chlorine atom lacks one electron of the number required for satisfaction in configuration. Hence, each atom shares one of its electrons with the other atom of its molecule. The requirements of configuration are thus satisfied, and in effect a pair of electrons is shared.

ness as did the first electron of the second shell, and hence, sodium, the eleventh system, has much the same properties as lithium, the third.

For similar reasons there is a periodic recurrence of the properties of beryllium when we reach the twelfth system, that is magnesium, and corresponding recurrences until we reach argon, where the shell has its complement of eight electrons. Again we have a stable structure.

A new shell, a fourth, is required for electrons in excess of eighteen. This may not be superimposed, as was the third shell upon the second, for these inner shells now hold too many electrons to permit so near a position for additional electrons. The fourth shell is presumably three times as far from the nucleus as is the first and hence its area is nine times as great and its capacity for electrons eighteen instead of two.

The first three of the atomic systems which are formed by the addition of electrons in this new shell also partake of the properties of the corresponding three in the two series previously considered. The area of the fourth shell is larger, however, and it is not filled until eighteen electrons are in it. The atomic system which exists when this fourth shell has four electrons has no such amphoteric properties as have silicon and carbon. It has no choice in its method of obtaining stability since to progress to stability would require the addition of fourteen electrons, while to regress would require only the loss of four. Similarly the next atomic system, with five electrons in this shell, can have only a positive

valence. To assume the nearest stable structure, that of argon, would require the subtraction of all five electrons.

Here we are met by a choice of kinds of satisfactions. A satisfaction of configuration requires the loss of five electrons. As each electron is lost the unsatisfaction as to the discrepancy between numbers of protons and of electrons becomes more marked. As long as a net balance of satisfaction is attained by losing electrons there will be a tendency to do so. This balance of desires is generally met before all five are lost, for two and three are the usual valences of the vanadium system which we are considering.

TABLE II

THE NAMES AND NUMBERS OF THE ATOMIC SYSTEMS

| | | | |
|---|---|---|---|
| 18 | Argon* A | 37 | Rubidium Rb |
| 19 | Potassium K | 38 | Strontium Sr |
| 20 | Calcium Ca | 39 | Yttrium Y |
| 21 | Scandium Sc | 40 | Zirconium Zr |
| 22 | Titanium Ti | 41 | Niobium Nb |
| 23 | Vanadium V | 42 | Molybdenum Mo |
| 24 | Chronium Cr | 43 | ———— |
| 25 | Manganese Mn | 44 | Ruthenium Ru |
| 26 | Iron Fe | 45 | Rhodium Rh |
| 27 | Cobalt Co | 46 | Palladium Pd |
| 28 | Nickel Ni | 47 | Silver Ag |
| 29 | Copper Cu | 48 | Cadmium Cd |
| 30 | Zinc Zn | 49 | Indium In |
| 31 | Gallium Ga | 50 | Tin Sn |
| 32 | Germanium Ge | 51 | Antimony Sb |
| 33 | Arsenic As | 52 | Tellurium Te |
| 34 | Selenium Se | 53 | Iodine I |
| 35 | Bromine Br | 54 | Xenon* X |
| 36 | Krypton* Kr | | |

*Transition system

The names of the atomic systems with numbers between 18 and 54 are given in Table II. From this

it will be seen that the systems corresponding to those with 8, 9, and 10 electrons in the fourth shell, namely, those of atomic numbers from 26 to 28, are those of iron, cobalt, and nickel, the three elements commonly known as magnetic. They constitute a family of elements with much in common besides their magnetic property. Although they have about half as many electrons in their outer shells as is required for stability they have a sufficient number to form fairly symmetrical systems. Thus iron with eight electrons might have them disposed at the corners of a cube like that of the outer shell in neon or argon. Nickel also may attain considerable stability with its ten electrons. Their valences, however, would not be zero for the shells are incompletely filled.

These substances are not inert and yet they possess certain structural advantages over their neighboring systems sufficient to form an opportunistic goal, toward which these other systems may struggle in their quest of satisfaction in form. For this reason some of the systems on both sides of this group partake somewhat of their qualities. For this reason also, starting with the copper system, which is next higher than nickel, the valences again form an ascending series, being one (or two in some cases) for copper, two for zinc, three for gallium, and four for the amphoteric germanium.

Beyond germanium, where the shell lacks only four electrons of its complement, satisfaction is most easily obtained by adding electrons and attaining to the form of the inert, stable system of krypton (36).

The elements from arsenic (33) to bromine (35) correspond, therefore, to those immediately below the other inert elements of neon and argon. Thus bromine belongs to the same family and reacts in the same general way to its electronic surroundings as do chlorine (17) and fluorine (9).

In a similar manner the elements rubidium (37), strontium (38) and yttrium (39), which have atomic numbers immediately above that of krypton, tend to revert in configuration to that structure and thus to lose electrons just as do the corresponding systems of the preceding series, namely, potassium (19), calcium (20), and scandium (21).

Between the atomic numbers of 40 and 50 the general characteristics of the atomic systems correspond to those of the previous series for which the numbers are 22 to 32. Again we find the structures of higher number tending to reach satisfaction in configuration by assuming that of the next highest stable system. Thus iodine, the fifty-third system, would attain satisfaction in gaining an electron and becoming in form like xenon, the fifty-fourth, in the same manner as chlorine, the seventeenth, would assume the form if not the substance of argon, the eighteenth system.

Beyond xenon the names of the atomic systems are given in Table III. A new shell is now required and we imagine one with four times the diameter of the first, sixteen times its area, and a capacity for thirty-two electrons. The first six elements in this new series correspond to the first six in the two immediately previous series. The seventh, of atomic

number 61, is as yet undiscovered. Of the last seven, the one with an atomic number of 85 is also undiscovered. Otherwise the higher elements of this series are like those immediately below the transition systems of xenon and krypton.

TABLE III

THE NAMES AND NUMBERS OF THE ATOMIC SYSTEM

| | | | |
|---|---|---|---|
| 54 | Xenon * X | 74 | Tungsten W |
| 55 | Cæsium Cs | 75 | ———— |
| 56 | Barium Ba | 76 | Osmium Os |
| 57 | Lanthanum La | 77 | Iridium Ir |
| 58 | Cerium Ce | 78 | Platinum Pt |
| 59 | Praseodymium Pr | 79 | Gold Au |
| 60 | Neodymium Nd | 80 | Mercury Hg |
| 61 | ———— | 81 | Thallium Tl |
| 62 | Samarium Sa | 82 | Lead Pb |
| 63 | Europium Eu | 83 | Bismuth Bi |
| 64 | Gadolinium Ga | 84 | Polonium Po |
| 65 | Terbium Tb | 85 | ———— |
| 66 | Dysprosium Ds | 86 | Niton * Nt |
| 67 | Holmium Ho | 87 | ———— |
| 68 | Erbium Er | 88 | Radium Ra |
| 69 | Thulium Tu | 89 | Actinium Ac |
| 70 | Ytterbium Yb | 90 | Thorium Th |
| 71 | Lutecium Lu | 91 | Uranium XII Ur XII |
| 72 | ———— | 92 | Uranium Ur |
| 73 | Tantalum Ta | | |

* Transition systems.

Of the thirty-one atomic systems between xenon (54) and niton (86), the first seven (55-61) correspond to systems (37-43) and (19-25). The last seven (79-85) correspond in chemical properties to systems (47-53) and (29-35). Both the lower series, (19-35) and (37-53), have intermediate transition systems of which the iron-cobalt-nickel group (26-28) is the more noteworthy. These intermediate transition systems are believed to be somewhat analogous to the transition systems formed by the

inert gases in that they have fairly stable electronic configurations, but they differ by being chemically active because they are not completely satisfied as to configuration.

In the series which we are now considering there are two such intermediate transition groups, namely, (62-64) and (76-78). Of these the latter, representing osmium, iridium, platinum, is the more important. The other group contains three rare earths, namely, samarium (62), europium (63), and gadolinium (64).

Between these two intermediate groups of transition systems there are nine known and two unknown systems, (72 and 75). With the exception of tantalum (73) and tungsten (74) these are all rare earths—metallic elements with positive valences of three. The pictures of electronic configuration which have been proposed to account for the elements between (62) and (77) are not as yet generally accepted and need not be discussed.[1] It is perhaps sufficient to record the fact that chemical properties do not vary sharply with increase in number of planetary electrons when the shell has more than eight electrons, but is not within eight of its complement.

Beyond the last inert system, that of niton, there are only a few known systems, and the series termi-

[1] It should be noted, however, that Bury has recently proposed a modification, of the electronic patterns described above, which promises to account for the rare earths and their common value of valence. His hypotheses demand a slightly different arrangement of shells and admit of electrons in the outer shell when the next shell within is incompletely filled.

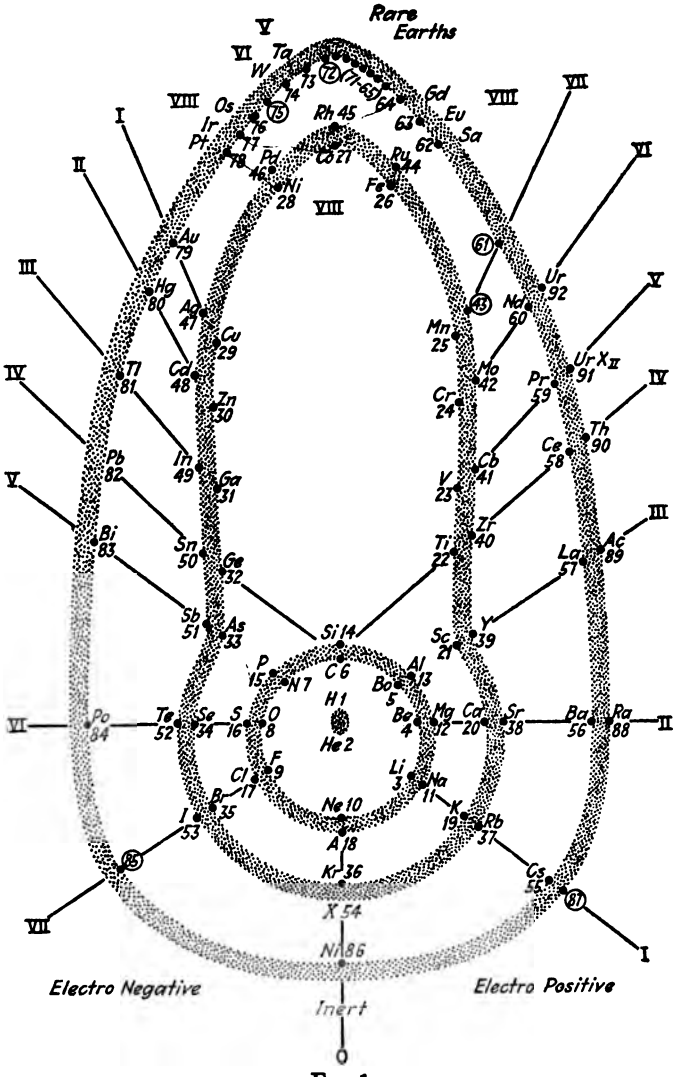


FIG. 1

Atomic systems at the periodic table. Place numbers correspond to atomic numbers. Systems similarly situated, as indicated by radial lines, have similar chemical properties.

nates with uranium from which by radioactive processes many of the lower systems were undoubtedly derived. These few remaining systems require electrons in a seventh shell, which we imagine to be superposed upon the sixth and to have the same capacity.

We may now make a schematic picture of the series of atomic structures as if there were a group of tables to be filled by guests. These tables are roughly concentric as shown in Fig. 1. One by one the atomic systems are seated and the order of their seating is given by the atomic numbers attached to their places. The first table seats only two. The next table eight on each side. The third table, seating eighteen on each side, must place some atomic systems in positions which do not correspond with any of those at the second table. There is, however, a correspondence between atomic systems which are opposite one another at the same table. The fourth table differs in some ways from any of the inner ones and on one side it is only partially filled.

In this representation atomic systems which have corresponding characteristics will be found to lie on the same radial line. That corresponding to the stable systems is marked zero. The others are marked with Roman numerals for the convenience of those who wish to compare with the usual tabular presentation of the periodic series of the chemical elements. Intermediate transition systems are indicated by VIII. To a very large extent the elements correspond in positive valence to the Roman numerals, thus the elements of group I all have positive

TABLE IV—PERIODIC TABLE SHOWING VALENCES

| O | I | II | III | IV | V | VI | VII | VIII |
|---|---|---|---|---|---|---|---|---|
| 2 He<br>*0* | 3 Li<br>*1* | 4 Be<br>*2* | 5 B<br>*3* | 6 C<br>*4, -4* | 7 N<br>*5, -3* | 8 O<br>*-2* | 9 F<br>*-1* | |
| 10 Ne<br>*0* | 11 Na<br>*1* | 12 Mg<br>*2* | 13 Al<br>*3* | 14 Si<br>*4, -4* | 15 P<br>*5, -3* | 16 S<br>*6, -2* | 17 Cl<br>*7, -1* | |
| 18 A<br>*0* | 19 K<br>*1* | 20 Ca<br>*2* | 21 Sc<br>*3* | 22 Ti<br>*2, 3, 4* | 23 V<br>*2, 3, 5* | 24 Cr<br>*2, 3, 6* | 25 Mn<br>*2, 3, 4, 6, 7* | 26 Fe, 27 Co, 28 Ni<br>*2, 3, 6, 2, 3, 4, 2, 3* |
| | 29 Cu<br>*1, 2* | 30 Zn<br>*2* | 31 Ga<br>*3* | 32 Ge<br>*4, -4* | 33 As<br>*5, -3* | 34 Se<br>*6, -2* | 35 Br<br>*7, -1* | |
| 36 Kr<br>*0* | 37 Rb<br>*1* | 38 Sr<br>*2* | 39 Y<br>*3* | 40 Zr<br>*4* | 41 Nb<br>*2, 3, 4, 5* | 42 Mo<br>*2, 3, 4, 6* | 43 | 44 Ru, 45 Rh, 46 Pd<br>*2, 4, 6,*<br>*2, 3, 4, 6, 8 1, 2, 4* |
| | 47 Ag<br>*1* | 48 Cd<br>*2* | 49 In<br>*3* | 50 Sn<br>*4, -4* | 51 Sb<br>*5, -3* | 52 Te<br>*6, -2* | 53 I<br>*7, -1* | |
| 54 X<br>*0* | 55 Cs<br>*1* | 56 Ba<br>*2* | 57 La<br>*3* | 58 Ce.<br>*4, 5* | 59 Pr<br>*4, 6* | 60 Nd<br>*4, 5* | 61 | 62 Sa, 63 Eu, 64 Gd<br>*3 3 3* |
| | | | | | | | | |
| | | | | | 73 Ta<br>*3, 4, 5* | 74 W<br>*2, 4, 5, 6* | 75 | 76 Os, 77 Ir, 78 Pt<br>*2, 3, 4, 6*<br>*2, 3, 4, 6, 8 2, 3, 4* |
| | 79 Au<br>*1, 3* | 80 Hg<br>*1, 2* | 81 Tl<br>*1, 3* | 82 Pb<br>*1, 2, 4* | 83 Bi<br>*2, 3, 4, 5* | 84 Po<br>? | 85 | |
| 86 Nt<br>*0* | 87 | 88 Ra<br>*2* | 89 Ac<br>? | 90 Th<br>*4* | 91 UrXII<br>? | 92 Ur<br>*2, 3, 4, 5, 6* | | |

valences of one although copper may also have two and gold may have three as values of valence. For groups beyond IV, the exceptions become more frequent as is evident from Table IV, where the periodic series is tabulated. This table gives for each element, except for some of the rare earths, the atomic number, the chemical symbol and the various observed valences.

# CHAPTER IV

## MASS AND INERTIA OF ATOMIC SYSTEMS

THE physical matter of which we are composed and with which we deal whether as scientists or not is composed of discrete molecules which are but unions of smaller particles, the atomic systems. Of the latter, we have distinguished ninety-two types which differ in the number of excess protons in their nuclei and consequently also in the number and configuration of the planetary electrons about their nuclei. Because these external electrons are all identical, the various atomic systems form a progressive series of geometrical patterns in which certain typical relations periodically recur. The series, therefore, contains groups or families of atomic types, which possess similar or common characteristics.

Although the actual configurations are not known, the hypothetical scheme of disposition for the planetary electrons, which was presented in the last chapter, accounts for a sufficiently large number of the known relationships of atoms to warrant its tentative acceptance. About the nucleus the electrons are grouped as if they occupied cells in shells of diameters which are related as 1:2:2:3:3:4:4 and of capacities for electrons, 2, 8, 8, 18, 18, 32 and 32 re-

spectively. No electrons exist in outer shells unless those within are completely filled. Those systems which have no partially filled shells are satisfied inert structures to whose configuration the unsatisfied systems tend to revert or to progress. In this tendency is the proximate cause of the chemical actions of various kinds of atoms.

The basis which has been chosen for the classification of atomic systems is relative in that it depends upon the excess of protons in the nucleus over the electrons and not at all upon the total number of either kind of electrical element. It is therefore possible that two or more atomic systems may exist which classify as of the same type, that is are isotopic at the Periodic Table, but differ in the total number of protons in their nuclei. In all chemical combinations or reactions these isotopes are indistinguishable. They may be distinguished, however, as the result of an important physical property of electrical elements which is most pronounced in the case of protons.

This property is that of inertia, the inherent unwillingness to change in state of motion which is common not only to the infinitesimal elements but to such larger aggregations as compose ponderable objects, whether human or otherwise. It is this quality which makes the flying missile so destructive and the stone wall or conservative so annoying. The first delivers a blow and the second resists our force and impedes our progress.

Because of the phenomenon of gravitation we have become accustomed to measure inertia by weight

and a popular misconception has arisen in which weight, mass and inertia are inextricably confused. The difficulty is largely due to our instinctive approach to scientific questions through our immediate but frequently misleading sensations.

When we cause a body to alter its state of motion, either by changing its speed or its direction, we are conscious of exerting what we are pleased to call a force. When we observe the gravitational tractation of body and earth we speak of a force of gravitation as acting on the body. Bodies upon which the earth under similar conditions exerts equal forces we call equal in weight. Unfortunately weight is but a particular kind of force and force itself is an entirely subjective concept without any objective reality. Whatever may be the character of the alteration in the relative motions of the bodies of a system the alteration is but the manifestation of a change in the disposition and availability of that uncomprehended motive power of our universe which we call energy.

Energy and the electrical elements are the postulates of the new science, the entities in terms of which all explanations of scientific phenomena must be made.

To our senses, whether aided by apparatus or not, this motive power, or energy, is evidenced only by changes in the state of motion of the electrical elements. To every moving particle, whether electron, proton, atom, molecule, or more evident mass, we ascribe a portion of this unknown. The amount which we assign to any particle depends upon the

speed with which it is moving and upon its electrical composition.

As the unit by which to measure energy we may take that energy which is associated with an electron under some definite and arbitrarily chosen condition of motion. For example, we might choose the speed of one centimeter a second as that at which an electron would be traveling when it had what we wish to call a unit amount of energy. Two electrons moving with this speed, obviously, represent two units of energy.

When two bodies differ in kinetic energy[1] even though their speeds are alike we say that they differ in inertia or in mass. In quantitative significance the two terms are interchangeable although the first represents the unwillingness of a body to change its state of motion and the second the quantity of matter in the body. On the basis, for example, of experimental observations of the relation for the energies of any body and of an electron we may ascribe to the body a mass which is some definite number of times that of an electron.

If we are to express quantitative relationships we shall need units. Three fundamental units are all that are required and these have already been chosen. They are the units of distance, time, and energy. Our unit magnitudes are then the centimeter, the second, and the kinetic energy of an electron which is moving one centimeter per second.

The habit of reducing all quantitative expressions

[1] That is, energy associated with a body as consequence of its motion.

to terms of a very limited number of units is not restricted to scientific procedure but holds in many other human activities. To a large extent we measure our desires and their gratification in terms of the distance we would go, the time we would consume, and the money we would expend.

There is a wide range of choice in the selection of magnitudes upon which to base three fundamental units, but for present purposes the three previously mentioned are to be preferred. In terms of these we may define unit mass. First, however, we recognize that a speed of one centimeter per second is a speed of unit distance in unit time, that is a speed of unity. Double the distance in the same time or the same distance in half the time represents a speed of two units. In terms of units of speed we now see that our chosen unit of energy is that associated with an electron which is moving with unit speed. The next step is to define unit mass as that of a body which has unit energy when its speed is unity.

It is to be noted against future reference that this definition carries no implication as to the constancy of mass and contains no indications as to the relationship of mass, speed, and energy.[1] The consideration of these matters may be omitted since our immediate discussion requires only the recognition of mass as a factor for expressing the relation of the energies of two bodies whose speeds are identical.

We assume that energies are determinable and that speed is not only measurable but controllable so that we may determine the mass of a body by

[1] For such a relation *cf.* p. 205 in the Appendix.

finding its energy at unit speed. When so determined the mass of an alpha particle is 7380 times that of the electron. The alpha particle, however, is merely the nucleus of the atomic system known as helium. When associated with two planetary electrons it becomes an atom of helium. The mass of the atomic system of helium, therefore, is due almost entirely to this nucleus.

Alpha particles are known to be constituents of the nuclei of all radioactive atomic systems and are assumed to be present in all other systems except hydrogen. It seems highly probable, therefore, that within the nucleus of any atomic structure the protons are associated in groups of four, bound together with two electrons in the same manner as in the alpha particle. Whenever the number of protons in the nucleus is divisible by four we may, therefore, expect, although we do not yet know, that the nucleus is formed by an integral number of alpha particles.

Consider, for example, such a nucleus as would be formed by four alpha particles. Each constituent contributes four protons and two electrons so that the nucleus contains a total of sixteen protons and eight electrons. Its atomic number would then be eight, that is, its construction would correspond in valence and in other chemical properties to the atom of oxygen. Its mass would be due to four alpha particles and would be four times that of the helium atom, and this, in fact, is the experimentally determined ratio for the masses of the oxygen and helium atoms.

A nuclear composition of only alpha particles is not possible, however, where twice the atomic number is not evenly divisible by four. In such cases we must assume the nucleus to contain [1] in addition to alpha particles one or more protons. In the case of nitrogen, for example, it has been determined recently that protons are part of the nucleus for they may be knocked out from the nuclei of nitrogen atoms by impacts from other atomic systems which are moving with enormous speeds.

In determining the mass of an atom we may neglect the electrons and assume that each proton contributes to the nucleus one-quarter of the mass of an alpha particle. For any nucleus, then, we may calculate the mass as some improper fraction of the mass of an alpha particle. For example, if an atomic system has twenty-two protons in its nucleus it has a mass of 22/4ths of an alpha particle. We may compare the mass also to that of an atom of oxygen. Since the latter is four times as heavy as the helium atom, the mass of the system which we are considering is 22/16ths that of an oxygen atom. In addition to the system with twenty-two protons let us assume another which has twenty protons. Its mass will be 20/16ths that of an oxygen atom. Instead of working with fractions we shall let 16 stand for the mass of an atom of oxygen and then in terms of the new unit thus arbitrarily adopted we may express the masses of the hypothetical systems as 22 and 20 respectively.

So far we have been concerned only with their

[1] *Cf.* footnote of p. 114, and also p. 111.

masses. Now let us assume that they are of the same type, each with an atomic number of ten. The configuration of the ten planetary electrons will then be the same in both structures; the valence will be the same; the chemical properties will be the same; and the only difference will be in mass. The isotopes, which we are imagining, cannot be separated by chemical methods for they have identical behaviours in all reactions.

Let us further suppose that this chemical identity has resulted during the ages past in such a mixing of these isotopes that wherever one obtains a sample of this chemical element the sample will contain them in the same proportion. Suppose, for example, that there are nine atoms of the isotope with mass 20 for every one of that with mass 22. Any determination of the atomic mass will give the average mass, that is 20.2, since on the average the total mass of ten atoms would be $9\times20+1\times22$ or 202.

We now turn to Table V in which are given for some of the chemical elements their so-called atomic weights, on the basis of 16 for the oxygen atom. For neon, which we know to have an atomic number of ten, the atomic weight is 20.2. The gas which the chemists used to know as neon is not a homogeneous gas, composed of identical atoms, but is a mixture of two gases, the atoms of which are alike in atomic number but unlike in mass.

These two isotopes, of atomic weights 20 and 22, have recently been isolated by physical rather than chemical methods. The methods used are made possible by the fact that systems which differ in mass

will have different energy contents at the same speed. As we shall see later, however, the actual experimental determinations are based on the converse statement of this relationship; if two particles of different masses are given equal energies they will differ in speed, the smaller mass attaining the greater speed.

The table of atomic weights, to which reference

TABLE V

ATOMIC WEIGHTS OF SOME COMMON CHEMICAL ELEMENTS

| | | | |
|---|---|---|---|
| Hydrogen | 1.008 | Copper | 63.57 |
| Helium | 4.00 | Zinc | 65.37 |
| Lithium | 6.94 | Arsenic | 74.96 |
| Beryllium | 9.1 | Selenium | 79.2 |
| Boron | 11.0 | Bromine | 79.92 |
| Carbon | 12.0 | Krypton | 82.92 |
| Nitrogen | 14.01 | Rubidium | 85.45 |
| Oxygen | 16.0 | Palladium | 106.5 |
| Fluorine | 19.0 | Silver | 107.88 |
| Neon | 20.2 | Cadmium | 112.4 |
| Sodium | 23.00 | Tin | 118.7 |
| Magnesium | 24.32 | Antimony | 120.2 |
| Aluminum | 27.1 | Iodine | 126.92 |
| Silicon | 28.3 | Xenon | 130.2 |
| Phosphorus | 31.05 | Cæsium | 132.81 |
| Sulphur | 32.06 | Barium | 137.4 |
| Chlorine | 35.45 | Tungsten | 184. |
| Argon | 39.9 | Osmium | 190.9 |
| Potassium | 39.10 | Iridium | 193.1 |
| Calcium | 40.1 | Platinum | 195.2 |
| Manganese | 54.93 | Gold | 197.2 |
| Iron | 55.84 | Mercury | 200.6 |
| Nickel | 58.68 | Lead | 207.2 |
| Cobalt | 58.97 | Bismuth | 208.0 |

NOTE: The following elements have isotopes of the following atomic masses:

Lithium, 6, 7
Boron, 10, 11
Neon 20, 22
Magnesium 24, 25
Silicon 28, 29
Chlorine 35, 37
Potassium 39, 41
Bromine 79, 81
Rubidium 85, 87
Krypton 84, 86, 82, 83, 80, 78
Xenon 128, 130, 131, 133, 135
Mercury (197-200), 202, 204
Lead, Bismuth—*See* Fig. 2.

has been made, gives the observed relation between the masses of the atoms of various chemical elements as determined by the weights of equal numbers of atoms. To facilitate the expression of the relations or ratios of atomic mass the ratios are all referred to oxygen and a common denominator of 16 is used in their expression. The various numerators of the ratios then become the atomic weights of the various elements in terms of oxygen as 16. The choice of this number was a more or less conscious anticipation of the facts of today. The unit of weight which is used in the expression of atomic weights is the weight of one-sixteenth of the oxygen atom. Today we know that this unit is the weight, or more strictly the mass, of a proton which is associated with other protons and electrons in the nuclear structure of an atom. To a close approximation this unit of the table of atomic weights is one-quarter the mass of an alpha particle and hence is 1845 times the unit of mass which was chosen earlier in this chapter.

For reasons which are not yet evident the mass of an *isolated* proton is not exactly one-sixteenth of the mass of an oxygen atom. Relative atomic weights are capable of sufficiently exact determination so that the values in the table are not to be doubted. From that table the masses of the atoms of hydrogen, helium and oxygen are respectively 1.0008, 4.00, and 16.00.

Why hydrogen is not unity is not known, although plausible explanations may be given in terms of electro-magnetic theory. When, however, we consider that mass is merely a factor in the expression

of the relationship between energy and speed, it becomes conceivable that the energy relations [1] should be slightly different, depending upon whether or not the proton is nearly or entirely isolated or is intimately associated with other protons as in the nuclei of the atoms of large mass and large atomic number.

Whenever the atomic weight of a chemical element is a whole number within the limits of the experimental errors involved in its determination, as, for example, in the cases of lithium, nitrogen, sodium, and sulphur, we have reasons to expect that the substances are actually chemical elements and not mixtures of atomic systems with equal atomic numbers but unequal nuclear masses. In all other cases isotopes are suspected and recent experiments have shown the existence of the proper isotopes to explain the failures of some atomic weights to be whole numbers. The isotopes so far discovered are given in the note to Table V.

One of the most interesting illustrations of the existence of isotopes is found in the case of lead, where a large number are known to exist, for lead seems to be an end-product of several different series of radioactive disintregations which we shall consider in the next chapter.

[1] As a matter of fact, or rather as a consequence of the theory of relativity, mass is more than stated above—it is energy itself. Larger mass means larger energy. Four discrete protons have a total energy of 4 times 1.0008 but when combined into an alpha particle their total energy is only 4 times 1. In the act of combination energy is released and on this basis astronomers expect a solution of the baffling problem of the source of the sun's energy.

# CHAPTER V

## RADIOACTIVE DISINTEGRATIONS

ATOMIC systems which are chemically identical and non-separable occupy the same place in the periodic table which was described in Chapter III. The basis of selection for position is the atomic number. Systems with the same atomic number may, however, differ in atomic mass, in previous history, and in inner tendencies toward radioactive displays. When the atoms of such isotopic systems are different in mass they may be separated by physical means, but those of isotopic systems which differ in inner tendencies cannot be separated. When, however, their divergent tendencies actually result in different radioactive transformations we may reason that isotopes do exist.

Radioactive substances have been described as atomic systems which are dissatisfied in their nuclear structures. In an individual atom such dissatisfaction leads to a nuclear debacle, after which the atom is generally declassed. Ultimately all the individual atoms of a radioactive substance will undergo the same transformation. By some inner economy, however, they so arrange that at any instant a definite proportion of their number shall be engaged in the characteristic activities of the group, that is

either hurling alpha particles or shooting forth at high speeds the lighter beta particles.

When an atom changes in its nuclear construction it must be reclassified and assigned to another place in the periodic table. By radioactive changes the atom jumps from one place in the table to another. The new atomic system, which embraces the atoms which have jumped, differs in previous history and inner tendencies from the system which already occupies the new place in the periodic table. With this older occupant it becomes isotopic but not identical.

The changes in position in the periodic table which accompany radioactivity are due to changes in the nuclear structure of the various atomic systems. The nucleus may lose an alpha particle or a beta particle. A loss of an alpha particle reduces the number of protons in the nucleus by four and the number of electrons by two. The excess of protons over electrons, which we express by the atomic number, is therefore reduced by two. Whenever a nucleus loses an alpha particle the atom is declassed, not to the class immediately below but to that two below in the scale of atomic numbers.

When an atom of radium loses an alpha particle it ceases to be radium, for its atomic number is reduced from 88 to 86. This new substance is called niton, or "radium emanation." In a similar manner when an atom of niton loses an alpha particle it becomes isotopic with all other systems of atomic number 84.

Before discussing this series of changes it is de-

sirable to consider for a moment what happens to the alpha particle which is ejected. It is the nucleus of a helium atom and needs two external electrons to become a satisfied, inert helium atom. In the first portion of its mad rush outward from a radioactive atom, an alpha particle seriously disturbs the other atomic systems by which it passes, shaking and knocking loose some of their planetary electrons. Its effect is to ionize some of the atoms of the atmosphere through which it passes, forming atomic systems which are unsatisfied in number of electrons, some having too few and others, which have acquired the loosened electrons of their neighbors, having too many. When the rush of the alpha particle has been stayed it, too, becomes as the other atomic systems of the atmosphere and finds quantitative satisfaction by claiming two electrons from any system which has more than it needs for its own satisfaction.

The subject of the ionization of gases by alpha particles, and also by other methods, is one of considerable interest but it must be postponed. For the present it must be sufficient to say that in the atmosphere of the earth there are always some atomic systems which have either an excess or a deficiency of electrons. Whenever in the wanderings of these systems those of opposite kinds of unsatisfaction meet an electron is transferred.

The fierce rush of the alpha particle, as it is ejected from the nucleus of the radioactive atom, is capable of dislocating the planetary electrons of the atom from which it proceeds just as well as those of other

atoms which it meets later. Its departure from the nucleus leaves the nucleus a net excess of protons two less than before, and the shells of planetary electrons would therefore have an excess of two electrons, if the alpha particle did not jar them off into outer space. It is not content, however, with shaking loose enough planetary electrons to leave the remaining atomic structure neutral, that is satisfied in total number of protons and electrons. It appears to dislocate several electrons and so to leave behind it an atomic structure reduced by two in atomic number and by more than two in number of planetary electrons.

The effect is experimentally observable because of the phenomenon of recoil. When the alpha particle erupts, it kicks back the structure from which it proceeds. Because of the larger mass of the system which is left the speed of its recoil is much less than that of the lighter alpha particle. It suffices, however, to permit a segregation of the two products of a radioactive disturbance.

The electrons, which the departing alpha particle drags from its own original atomic surroundings, wander about as free electrons or are acquired by neighboring atoms which thus become quantitatively unsatisfied. From them, or from other structures with excess electrons, the atomic system, which results from the emergence of an alpha particle, may later acquire sufficient electrons to be quantitatively satisfied. The number which it thus adds will be such as to make the number of planetary electrons equal to the new atomic number. The disintegra-

tion product, therefore, of an emission of alpha particles is a substance with the atomic number and also the configuration of planetary electrons which correspond to a position in the periodic table in the second place below that occupied by the atomic system of the original substance. The atomic mass of the disintegration product is, of course, four units less than that of the original atom, because each alpha particle removes four protons.

An opposite type of change occurs when a beta particle is ejected from the nucleus of a radioactive atom. The atomic number is increased by one, since the excess of protons in the nucleus is increased by the subtraction of an electron. In the planetary system of the atom there is then a deficit of one electron over the number necessary for quantitative satisfaction of the system. An extra electron is required and it is shortly acquired perhaps from some atom which wanders into the neighborhood. The net result is an increase of one in the atomic number and a configuration of planetary electrons which corresponds to the new atomic number. The disintegration product of a radioactive change which is accompanied by the expulsion of an electron is therefore isotopic with the atomic system of number next higher than the original system. The expulsion of an electron, however, is unaccompanied by any appreciable change in mass, for we consider the mass of an atom to be due essentially to the protons which enter into its nuclear construction.

A glance at the diagrammatic representation of the periodic table which is given on page 33 shows

that the atom moves two places (clockwise) if there is expelled an alpha particle and one place (counter-clockwise) if a beta particle is expelled. Two successive expulsions of beta particles will therefore neutralize the effect of one expulsion of an alpha particle so far as concerns position in the table. It will not neutralize the change in mass, however, for the "beta ray" change, as it is called, is without effect on atomic mass, while the "alpha ray" change produces a reduction of four units in atomic mass.

It therefore happens that a radioactive substance may undergo such a succession of changes as to produce a substance isotopic with the original substance, chemically indistinguishable, but four units less in atomic weight. This is true, for example, in the case of uranium which ejects an alpha particle, forming Uranium $X_I$, as it is called. This substance ejects a beta particle, forming Uranium $X_{II}$, and the latter ejects another beta particle, forming Uranium II, so-called, which is isotopic with uranium.

Altogether some thirty-eight radioactive substances have been discovered. All these, however, find their places in the periodic table between uranium, with an atomic number of 92, and lead, with a number of 82. All are products of the disintegration of two elementary substances, uranium and thorium. Radium, the most famous, is a product in the disintegration series of uranium. In terms of these elements, uranium and thorium, modern science accounts for all the known radioactive products.

The inner structure and history of the atoms of

any radioactive substance are not the same for all. There are points in the series of uranium, for example, where two distinct disintegration products may be formed. The entire series with its several branches is shown diagrammatically in Fig. 2. Changes produced by alpha rays are indicated by heavy arrows, and those of beta rays by lighter ar-

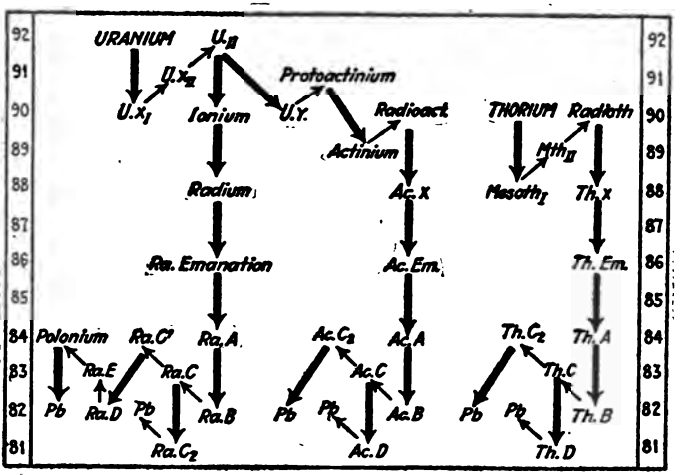


FIG. 2

Radioactive Transformations. Atomic numbers are given by the vertical scale. Alpha ray changes are indicated by heavy arrows. These decrease atomic number by two, and atomic weight by four. Beta ray changes are indicated by light arrows. These increase atomic number by one, but do not affect atomic weight.

rows. All the substances in the same horizontal line have the same atomic number but may have different masses.

From this diagram it appears that there is a relatively large number of isotopes of lead, for the end-products of the various series fall in the place at the periodic table which is occupied by lead with its

atomic number of 82. Under ordinary conditions what we know as lead is a mixture of several of these isotopes and has an atomic mass which depends upon the atomic masses and proportions of its constituents.

Several experimental studies have been made of lead derived from different mineral deposits to determine whether or not such differences in atomic weight actually existed and conformed to the probable radioactive antecedents. For example, an examination of the lead derived from Ceylon thorite gave 207.69 as compared to 207.2 which is the ordinary value. This mineral contains 55 per cent of thorium, 1 to 2 per cent of uranium, and about 0.4 per cent of lead, an amount so small as to be undoubtedly of radioactive origin. The lead in this mineral should be largely due to thorium unless the rate of disintegration of uranium is many times greater than that of thorium. Since it is only two or three times greater, the lead in this ore should be about ten parts of thorium origin for each part of uranium origin. Other similar experiments have been performed on samples of lead with different radioactive antecedents, and atomic weights have been obtained which range from 206.1 to 207.7.

Such experiments are but a small part of the careful, ingenious, and thorough study [1] of radioactive substances which has been responsible for the modern theory of isotopes. This theory has been corroborated by the discovery of isotopes among the

[1] To this study the chief contributions have been made by Soddy and Rutherford. To the former is due the concept of isotopes.

atomic systems of lower atomic number. Some results of such investigation were mentioned in the preceding chapter. The most potent method is that involving so-called "positive rays" but purely mechanical methods such as diffusion have been used to produce a separation of isotopes.

Within the last twenty years the whole basis for our conception of matter has changed. Today we know no matter but only electricity. Our atoms are no longer "uncut" but are complex structures of protons and electrons. Their masses are due to the protons and their chemical behaviour to the planetary electrons which encircle the nucleus. From the standpoint of chemical behaviour there are only ninety-two possible types of systems and these are distinguished by the excess of protons in their nuclei. Some of these types include structures of radically different atomic mass, history, and stability of nucleus. Those of unstable nuclear construction change from type to type in conformity with a definite law, shifting their positions at the periodic table of elemental types.

Such is the matter with which the new science deals. All phenomena of matter, such as cohesion, vaporization, capillarity, elasticity, heat conductivity, light and heat radiation or photochemical effects, must finally be explained in terms of a matter which is granular in structure and electrical in character. Unfortunately there remain today wide gaps in our knowledge. The first step, however, toward an appreciation of what is known is the consideration of those phenomena usually classified under the term "electricity."

# CHAPTER VI

## CONDUCTION OF ELECTRICITY THROUGH GASES

In the preceding chapters the discussion of atomic systems has been limited almost entirely to those systems which are quantitatively satisfied, so-called normal or uncharged atoms. The abilities of various atoms to enter into molecular unions with other atoms has been attributed to the unsatisfactory configurations of their planetary electrons. In the formation of such unions configurations are attained which represent net increases in satisfaction or stability. The molecules so formed are, of course, satisfied also in equivalence of electrons and protons and are normal molecular systems. Under certain conditions, of which Chapter II contained an illustration in the dissociation of sodium chloride, a molecular system may split into two parts each of which preserves some satisfaction of configuration at the expense of a satisfaction in quantity. The separate parts are called ions; and one has an excess of protons while the other has an excess of electrons.

Whenever any body has an excess of protons, whether the body be of atomic size or as big as the earth, we shall say that it is "positively charged" with electricity; and similarly we shall call a body with an excess of electrons "negatively charged."

Of the various possible ways of charging a body with electricity we shall consider first the so-called frictional method which originally excited attention to the peculiar properties of amber.

Suppose two dissimilar substances are brought into close relations by rubbing. In general there will be an appreciable difference between the substances in the matter of what constitutes a satisfactory configuration for the electrons of their molecules, for one may have a greater need for electrons than the other. Although the surfaces may appear smooth the structure of their atoms is such that the act of rubbing two bodies together is really the act of crowding one planetary system into another or causing one to pass through the other. There is every opportunity for some of the electrons to be displaced from their own planetary systems and to join those of other nuclei. The molecules of the system which has the greater need for electrons will gain or that which would more willingly assume a configuration with fewer electrons will lose. The net result when the substances are separated is that one has more than its normal number and the other less; the first is negative and the second positive in charge.

The classical substances are glass and silk, or cat's fur and sealing wax. The first of each pair acquires a positive charge and the second a negative charge.

The act of separating the substances is done against the attraction of the excess protons of one body for the excess electrons which are being left behind on the other body. The act requires work for the charged bodies tractate. If free to move into

contact they will do so, and the electrons which were foisted upon the unsuspecting electronegative systems of one body will return to the electropositive systems of the other, restoring the quantitative equilibrium.

In their motion of returning to each other the charged bodies manifest energy. This energy is contributed during the act of separation, is potential while they are held apart, and is converted into kinetic energy as they move toward each other. At the moment of impact the kinetic energy of the electrified bodies is passed on to their invisible molecules, atoms, and electrical elements, contributing to them haphazard motions which we recognize as heat. Of such conversions or transferences of energy, however, more will need to be said later.

Because two oppositely electrified bodies will so move toward each other and thus manifest energy we say that they possess when held apart a potential energy. Since we believe that energy is indestructible we measure this potential energy either by the energy originally required to produce the separation or by that which may be derived from a return of the electrical elements to the normal condition of equal numbers of protons and electrons.

The return, however, need not be accomplished by the actual motion of the two oppositely charged bodies, which may indeed possess billions of normal atoms for every one which is charged. Any method which will transfer electrons from the negative body to the positive will bring about the original stable condition. To all methods we give the general name

of "electrical conduction" and to the medium through which conduction takes place we ascribe a characteristic of electrical conductivity. With some of the methods of obtaining conductivity and with the corresponding mechanisms for conduction the remainder of this chapter will deal.

Whether by some adaptation of the crude method of electrification by friction, or by such more efficient means as dynamo-electrical machinery offers, we may give opposite electrical charges to two bodies. Such a condition is conveniently evaluated as a magnitude, known as electrical potential, which represents the potential energy of the last electron to be added to the negative body, and hence the energy which is released by the return of this electron to its former home. There is something of the idea of marginal utility in this concept of electrical potential for we always measure it by the energy corresponding to the last electron to be added. The comparison, however, is without stigma.

Whatever path this marginal electron may travel in a return trip the total amount of energy thereby converted from potential into kinetic is always the same and its value is the electrical potential between the two charged bodies. The movement of an electron from a negative to a positive body is a descent from a height, from a place of high potential energy to a place of zero possibilities in energy. As it falls it acquires kinetic energy and the potentialities are decreased. In steep places the conversion is rapid, not necessarily with respect to time, but rather with respect to space. Just as we measure the

grades of roads in feet of descent per mile of length, so we measure the "potential gradient" by the decrease in potential for each centimeter. In all the phenomena of conduction of electricity the important magnitude is this potential gradient, for it is the space rate at which a body, carrying an excess proton or an excess electron, will acquire kinetic energy.

If conduction occurs between two oppositely charged plates it may take place, depending upon the conditions, in any one or any combination of three distinct manners. There may be a motion of electrons from the negative plate to the positive, a motion of protons in the opposite direction, or a friendly service on the part of molecular or atomic systems which lie between the two plates. The last case is that of conduction through gases and also through conducting liquids such as the salt solution to which reference was made earlier in this chapter.

Ordinarily an atom or a molecule of a gas is incapable of assisting in electrical conduction. To serve, it must be ionized, that is be split into two parts which are quantitatively unsatisfied, one part positive and the other negative.

In any gas the various molecules are always in more or less violent haphazard motion. The greater the temperature the higher the speed with which they are moving, for temperature is merely our conventional term for expressing the degree of thermal agitation of the molecules of a substance. Each molecule travels in a straight line until its approach to another molecule causes it to swerve. There is no

real collision but rather a respect for each other's sphere of influence which results in a mutual change of direction when these spheres are in danger of collision. On the average between successive adaptations to the presence of its neighbors a molecule travels a distance relatively large as compared to its own size.

Now let us suppose that in the space between these widely separated molecules there are some free electrons, that is electrons which have been dislodged from their original atomic systems. These also wander about, choosing the easiest way and usually avoiding difficulties although an individual electron may now and then strike into the planetary system of a molecule and become attached to it.[1] If it does we have a negatively charged molecule; if it does not we have a free electron. In either case we have a very different phenomenon as soon as this gas is placed between two plates which are oppositely charged. Then there is added to the haphazard motion of the free electrons, or of those molecules which have acquired a negative charge by adding an electron, a directed motion due to the charged plates. Only those molecular systems which are uncharged are uninfluenced.

Each of the charged molecules or ions, as they should be called, now finds itself at some point or other along a path between the plates and starts to fall from this point toward the positively charged

[1] Whether or not the atoms or molecules of the atmosphere acquire these wandering electrons depends upon their type. Inert gases certainly can not; gases like oxygen, however, can because their atoms have external shells incompletely filled by electrons.

plate. If the potential gradient is small the result is merely a drift of the negative ions and electrons toward this plate as a goal. A possible comparison is the guided drift of a herd of cattle which a rancher is leisurely driving across the plains.

The larger the potential gradient at any point, that is the more rapidly a negative ion or an electron falls toward the positive plate, the greater is the possibility of its plunging into the atomic system of some molecule, which may be in its path, and generally dislocating this system. If it falls far enough to acquire a certain definite amount of energy it will knock[1] an electron loose from the molecule with which it collides, and then continue on its own way toward its positive goal. As soon as it has again fallen far enough to acquire the necessary energy it is ready to ionize another molecular system.

Each time it does so it leaves behind a free electron and a positive ion, that is a molecular system which has lost an electron and so has an excess of protons. These also take up directed motions, the electron moving toward the positive plate and the positive ion moving in the opposite direction. Both of these newly formed systems are able to ionize uncharged molecules with which they collide provided that between successive collisions they fall sufficiently far to acquire the necessary amount of energy.

The process is obviously cumulative; and what starts as a drift of the occasional unemployed electron becomes a stream of oppositely directed and op-

[1] The word "knock" is convenient although "crowd" is more exact for there is no actual contact in a "collision."

positely charged particles, both ions and electrons. A current of electricity is now said to be flowing between the two plates. The net effect of the motions of these ions and electrons is to carry protons to the negatively charged plate and electrons to the positively charged plate. When a positive gaseous ion reaches the negative plate it acquires from it an electron which satisfies its own requirement and reduces the unsatisfaction of the negative plate. Similarly the electrons which arrive at the positive plate join its atomic systems and reduce their unsatisfaction.

In describing this general phenomenon of the conduction of electricity through gases we have assumed, first, the presence in the gas of some free electrons or negative ions, and second, a potential gradient between successive collisions such that these ions acquire sufficient energy to ionize the gas molecules with which they collide.

The first condition is always met by the atmospheric gases above the earth, for it so happens there is a sufficiency of radioactive transformations[1] always going on within the earth to provide a fair number of electrons in each portion of the atmosphere. These electrons are wrenched from their original atomic systems by the so-called gamma rays which usually accompany the beta rays. While the beta rays are not rays at all but are expelled electrons the gamma rays are strictly a radiation of energy

[1] Electrons are also freed in large numbers by the ultra-violet rays from the sun. This is a more important source. The phenomenon is mentioned later and also considered in detail in Chapter XI.

similar to light radiation, but most closely allied to X-rays. Ordinary matter is not very opaque to these radiations, which are extremely penetrating and thus ionize gases far from their source. The second condition is usually within the control of the experimenter, for electrical potentials of a wide range of values are possible by the use of electric batteries or dynamos.

The amount of energy which must be acquired by an electron or ion in order, by its impact, to ionize a normal molecule or atom is dependent upon the character of the latter. It is obvious, for example, that the ionizing potential which is required for the disruption of an atom of helium, or of any other inert gas, into a free electron and an atomic system which is positive by virtue of a lost electron, will be greater than that required for the ionization of some electropositive element, like sodium, where the system contains one electron more than its most stable configuration would require. The ionizing potential depends upon the electronic configuration of the atom or molecule in much the same way as does the chemical valence.

There are many interesting phenomena connected with the conduction of electricity through gases which merit and will receive later some discussion. For example, the oppositely directed streams of positive and negative ions may have collisions among themselves which result in the formation of uncharged molecules. On the other hand, the impacts of collision may be insufficient to cause ionization and yet be sufficient to cause such a readjustment

of the electronic constituents of the atom as to result in a radiation from it of light with a characteristic color. The characteristic radiation which is emitted by the molecules of the gas is not entirely visible to the human eye for some of it lies beyond the violet. These ultra-violet radiations are capable of shaking loose electrons of substances upon which they impinge. When, therefore, they strike the negative plate and so shake loose electrons from some of its atoms, the freed electrons are repelled from the plate into the surrounding gas where they take paths toward the positive plate.

At the negative plate electrons may be freed if the impacts of the positive ions are sufficient to disrupt the atomic systems of which the plate is composed. The bombardment of the plate results also in a general thermal agitation of its constituents which is manifested by a rise in temperature.

Before discussing some of these phenomena in more detail a few words should be devoted to that type of conduction which occurs when molecular systems dissociate in solution. The example which was given earlier is that of sodium chloride. Quite a large group of chemical compounds will dissociate in this manner and these are known as ionogens or electrolytes. They may be divided further into three classes. The first of these, known as acids, give as one product of the dissociation positively charged ions which are nothing more or less than protons, although they are commonly known as hydrogen ions. They are hydrogen atoms which have each lost an electron to their previous partners in molecular

union. An example would be hydrochloric acid, HCl. The second type yields negative ions, $\bar{O}H$, which are composed of one oxygen and one hydrogen atom in a molecular union, but have retained one electron from their former associates. Such compounds are called bases. An example is sodium hydroxide, that is, caustic soda, which is symbolised as NaOH. The third type, known as salts, is the result of mixing solutions of an acid and a base. Under these conditions the positive and negative ions, $\dot{H}$ and $\bar{O}H$, combine, as often as they meet, to form $H_2O$ and the other ions when they meet form molecules of a salt which may or may not be soluble. Of this type NaCl is an example.

The dissociation is not the result of collisions or of ionization in any way similar to that discussed above for gaseous molecules. It is in the nature of a spontaneous parting of the molecular system because of the attracting influences of the neighboring molecules of water. The ions then pursue haphazard paths in the same way as do all the molecular systems which compose the liquid. If oppositely charged plates are immersed in the electrolyte, the ions are given directed motions in addition to their own natural haphazard motions. The positive ions proceed to the negative plate and the negative ions to the other plate. When they make contact with these plates their quantitative unsatisfactions are appeased and they become uncharged atomic or molecular structures. In this form they are either deposited on the plates or liberated as bubbles of gas.

With certain electrolytes there may occur secondary chemical reactions so that the substance which is liberated at the plate is not that which traveled through the solution as an ion. For example, when the electrolyte is dilute sulphuric acid, that is $H_2SO_4$ and $H_2O$, the two hydrogen ions, each $\dot{H}$, travel to the negative plate and there are liberated as hydrogen gas. The sulphate radical, $\bar{S}\bar{O}_4$ after delivering two electrons to the positive plate, combines with a water molecule to form more sulphuric acid. The oxygen atom thus released then joins with another atom of similar experience to form a molecule which appears as oxygen gas, $O_2$. By means, therefore, of the electric current and the secondary chemical action, water is decomposed into its chemical constituents.

# CHAPTER VII

## CONDUCTION THROUGH SOLIDS AND OTHER ELECTRICAL PHENOMENA

In solid bodies the molecules or atoms are restricted in their motions and do not wander from one part to another as do the molecules of liquids and gases. Through solids, therefore, the conduction of electricity can occur only as the result of the motion of electrons. The solid substances which conduct electricity best are metals, the elements whose atoms are most prone to part with an electron. These require the smallest potential relative to the ensuing stream of electrons.

The atoms of metals apparently do not form polyatomic molecules, so that in conduction through metallic solids we have to do only with atoms. The close grouping of atoms in solids is probably responsible for a certain freedom on the part of their electrons since it may mean that some of the planetary electrons of one atom are at times within the sphere of influence of another atom. In that case they might serve a dual purpose of partially satisfying the claim of their own nuclei and that of the adjacent atom. By such double service they would release other electrons of their respective atoms for more or less free wandering throughout the sub-

stance. The latter electrons would be akin in freedom to the molecules of a liquid and would be restrained from excursions beyond the solid by the attractions of the nuclei of the surface atoms. Under certain conditions, as we shall see on page 73, some may pass beyond the surface and appear in space as free electrons.

We might form a picture of a solid conductor of electricity by imagining an enormous basket ball court on which there are disposed a large number of players. Each is assigned to a relatively small circular space within which he is free to move. The space may, however, overlap somewhat those assigned to his neighbors so that even within his own circle a player's movements are sometimes restricted by the necessity of avoiding a collision with a neighbor. A large number of basket balls are being tossed rapidly about from player to player. The latter correspond to the atoms and the balls to the wandering electrons. There is always activity but the balls only fly wild, beyond the boundaries of the court, when there is a very considerable (thermal) agitation, as will be explained later.

Now suppose that each second we throw into the court at one end a large number of balls and withdraw an equal number from the opposite end. We do not alter the number within the court at any instant, but we do require that the haphazard motion shall be largely superseded by a directed motion. This in effect is what happens when there is a potential between the two ends of a solid conductor.

Each atom-player must pass to one of his neighbors who is nearer the positive goal.

Usually this is most effectively accomplished if the players are not dashing about too rapidly and moving too far. On the other hand, as the thermal agitation increases there seems to be more difficulty in securing the passage of the same current, that is the same number of electrons a second. A higher potential is required or there is a lower current for the same potential. Under these conditions we say that the conductor has a higher electrical resistance. For most substances the resistance increases as the temperature rises.

Conversely, as the temperature is lowered the resistance decreases. The decrease is a definite fractional amount for each degree of temperature, and indicates an extremely low temperature, at which we should expect no resistance but instead perfect conductivity. This temperature, which is the absolute zero and is discussed on page 173, has never been attained, although closely approached. It represents a condition in which there is no thermal agitation of the atoms of the substance. Under these conditions the atoms would be closely packed together and an electron could be passed from one to the other without requiring that it should ever pass beyond the influence of an atomic nucleus.

Under ordinary conditions it is believed that an electron shoots clear of its original atom and proceeds across free space until it comes into the sphere of another atom, just like the basket ball of our illustration. To free an electron from an atomic

structure requires an expenditure of energy and according to the most recent theory, that of Bridgman, the solid offers resistance because the electron must travel gaps between atomic systems. Within the sphere of influence of an atom the electron is believed to move freely. Upon this basis, and supported by many experiments, Bridgman is developing an apparently satisfactory theory of metallic conduction. According to this theory, when the atoms no longer dash to and fro they may be so close that an electron passes from one to the next essentially without crossing any gap.

Some substances, however, usually relatively poor conductors, decrease in electrical resistance as their temperature is increased. In such a case it is probable that the electrons are not so easily shot from one player to the next and a sort of hand-to-hand transfer is required. If the player-atoms are already too far apart for such an operation it may be facilitated by giving them greater amplitudes in their vibratory notions. This phenomenon occurs in the case of the carbon filament of the old-style electric lamp. When cold, and first connected to the electric light mains, it offers a larger resistance than it does a moment later when it is heated by the current.

Any conductor is heated by an electrical current. A stream of electrons can only be passed through a conductor as the result of an expenditure of energy upon the part of the system which establishes or maintains the potential. During the passage of a current the potential energy of the source is converted into kinetic energy of the carriers of the elec-

tricity—the electrons, in the case of solids. These by their impacts transfer to the intervening atomic structures the energy which they have acquired. Heat always results and sometimes light. In conduction through solids, however, light is always an indirect result of the increased thermal agitation and is not the direct result of recombinations of electrons with positive atomic structures, as it is in the case of conduction through gases. Light occurs as the temperature rises, and even melting may occur if sufficient energy is expended in the conductor.

Many degrees below the melting temperature, however, when the solid is red hot or incandescent, there is evident a phenomenon which well corroborates some of the statements made above. Suppose we have a wire, or rather a portion of it, in an evacuated vessel, as in the case of an incandescent lamp bulb, and heat the wire by an electric current. As the temperature increases the violence of the motions of the electrons, which serve for conduction, also increases. Remember that these motions are haphazard although they have a component in the direction of the positive plate. The progress of an electron along its course resembles that of the golf ball of an erratic but powerful driver, for more and more frequently as the temperature rises will some electrons be driven out of bounds. Those with sufficient energy and the proper direction of flight pass beyond the influence of the nuclei of the surface atoms and appear in the space beyond as free or dislodged electrons. An electron which is emitted in this way is sometimes called a "thermion."

Its behaviour is quite analogous to that of a molecule of a liquid. We know that evaporation is increased as the temperature of a liquid is raised and are inclined to think that it is restricted by enclosing the liquid. In a partly filled bottle, however, evaporation proceeds just as it would if the bottle were open except for the fact that the flighty molecules which evaporate have no place to go other than that immediately above the liquid. Here they soon become so congested that in dodging each other some of them get directed back toward the liquid surface. Striking that surface they take up again the normal routine of molecules in a liquid. If the temperature is maintained constant a condition of so-called statistical equilibrium is soon reached in which there are just as many molecules evaporating each second as there are condensing back into liquid form. The same sort of a statistical equilibrium exists when electrons are being thermionically emitted from a heated wire in a very highly evacuated space.

The equilibrium is displaced, however, if another wire or plate is inserted in the vessel and made positive with respect to the heated wire by proper connection to a battery or dynamo. Then, the electrons stream across the space to the positive plate, pass to the positive terminal of the battery and there appease to some extent the unsatisfactions which the activity of the battery elements manifest. At the same time other electrons from the battery pass along a wire to the heated electrode and thus maintain in it a normal supply of electrons.

This phenomenon was discovered by Edison many years ago although it was about thirty years before efficient application was made of the principles involved. Today it is widely used in wire and wireless communication, and also in electrical measurements in different types of industry, for the principle has been applied to the construction of an amplifier of electrical effects which is a veritable marvel of efficiency and delicacy.

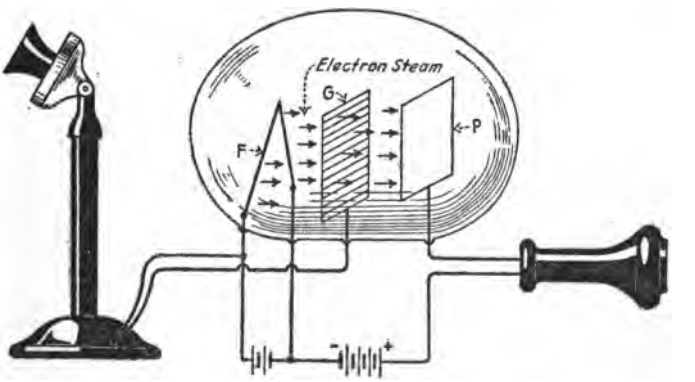


FIG. 3

The Thermionic Vacuum Tube. Electrons emitted by a heated filament, *F*, are drawn across a highly evacuated space to a plate, *P*. The stream is very sensitive to changes in the electrical potential of the grid, *G*. The device is widely used in the Bell System as an amplifier of telephone currents.

It is evident that, by the thermionic emission of electrons at a heated electrode, electrons are secured for the conduction of electricity through a vacuum. By the introduction of a third electrode the stream may be controlled with an inappreciable expenditure of energy. The result is that a very feeble electrical effect may manifest itself by a very pronounced

change in the current which passes through the vacuum. A device of this form is the "audion"—so-called by DeForest who introduced the third or controlling electrode. The combination of picture and diagram of Fig. 3 shows its practical features.[1]

We leave this phenomenon, however, to continue our discussion of electrical currents in wires and to develop some ideas which are essential to the later text. Except at high temperatures, where the electrons may be "boiled out," the course of the electrons is entirely controlled by the wire. Wires serve much like pipes for the guided flow of electrons and thus permit distinct streams of electrons to be brought very close to one another without merging.

This possibility is of great practical importance since parallel streams of electrons tractate. The tractation of parallel electron streams results in a tractation of the wires in which these streams are confined. Streams in opposite directions pellate and hence the wires which carry them are urged apart. If streams are at right angles there is no reaction between them. The phenomena, unfortunately, are as completely without explanation as are the fundamental phenomena of the tractation of proton and electron or the pellation of two electrons or two protons.

The effect depends for its magnitude upon the length of the wires which are parallel, the intensities of the currents, and the distance between the wires.

[1] The device has been highly developed both in structure and application by the research physicists and communication engineers of the Bell Telephone System and of the General Electric Company.

The greater the lengths which are parallel and the greater the currents, that is the greater the numbers of electrons which stream through the wires each second, the greater is the effect of attraction. It therefore happens that the effect may be enhanced by arranging each wire in the form of a coil, the successive turns of which will carry the same electron stream. Two coils of this solenoidal form are shown in Fig. 4. If they are supported so as to be free to

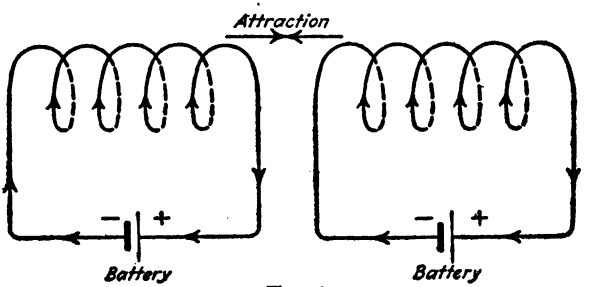


FIG. 4

Attraction of wires which carry parallel streams of electrons in the direction indicated by the arrows.

move it is found that they rotate so that their loops are parallel and at the same time they move closer together so that they tend to form one long continuous solenoid, the turns of which all carry parallel electron streams.

The effect is very greatly increased by winding the coils on cores of so-called magnetic material, for example, iron, cobalt, nickel, or certain alloys for which the electronic configurations are generally similar to those of these elements. The effect of the currents in the coils upon the atoms or molecules of the magnetic cores is easily explainable if we assume rota-

tions for some or all of the planetary electrons of an atom of a magnetic substance. Suppose some of the electrons are revolving about the nucleus. They constitute a stream of electrons around a loop just as really as do the streams which travel the larger loops of the solenoids which we have been considering.

Each molecule or atom of a magnetic substance will then act like a current-carrying loop and will tend to place itself so that its loop lines up with other

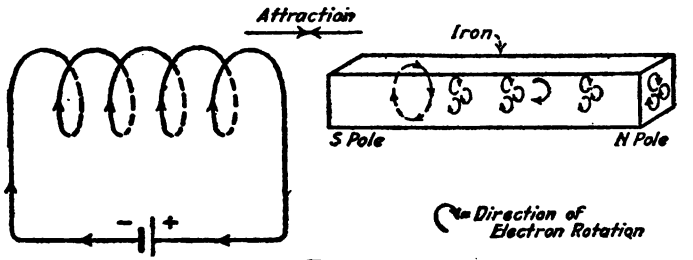


FIG. 5

Equivalence of a bar magnet and a current-carrying solenoid in phenomena of attraction.

current-carrying loops. The effect of the current in the solenoid is to orient the individual atoms or molecules of the core so that as many as possible of their loops shall be parallel to those of the solenoid. Under this condition the core is said to be magnetized, and the combination of core and exciting solenoid is called an electro-magnet.

The orientation which the molecules of the core acquire by virtue of the magnetizing current in the solenoid is retained with more or less tenacity after the current has ceased to flow. The core is thus made into a more or less permanent magnet. If its

ends are marked for reference and it is then withdrawn from the solenoid it will be found to replace a current-carrying solenoid and generally to behave as if it were a coaxial series of current-carrying loops. (See Fig. 5.) In all phenomena of mutual attraction or repulsion, magnets and current-carrying solenoids are equivalent.

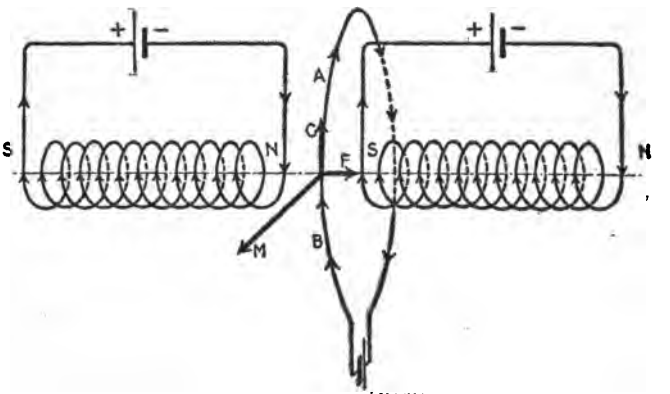


FIG. 6

Interaction of magnetic field and electron stream. The large current-carrying loop and the solenoid tend to place themselves coaxially. The effect is that the wire, *AB*, carrying the electron stream is pushed sidewise across the magnetic field between *N* and *S*.

In the case of magnetic materials we picture some or all of the planetary electrons as engaged in circular or elliptical motions. Adjacent molecules would then tend to orient themselves so as to have their current loops in parallel. We might therefore expect that in any piece of iron the molecules would of their own action have assumed such similar orientations as to have made the piece of iron a magnet. Such, however, is not the case. The mole-

cules have haphazard orientations, as may be verified by placing one piece of ordinary iron near another and noticing that there is no attraction or repulsion as there would be if the molecular currents were not flowing "every which way." The explanation is that the molecules have already formed themselves into a large number of small and fairly stable groups. For this reason heating and jarring, which increase molecular agitation, facilitate the process of magnetization of an electromagnet or the process of "self-demagnetization" by which its molecules reform self-satisfied groups which neutralize each other's external effects.

All so-called magnetic phenomena are merely the interactions of parallel streams of electrons. As far as possible current-carrying loops interact so as to place themselves parallel and coaxial and to have electron streams in the same sense, e.g. clockwise, or counter-clockwise, when viewed from a common point, not between the two loops. An application of this law, which is of importance in our later discussion, is shown in Fig. 6. If a portion of a current-carrying loop of large size is placed between two coaxial coils, which are carrying currents in the same sense, then the portion of the large loop is urged along a line at right angles to the axis of the fixed coils in a direction depending upon the direction of the current. The coaxial coils may contain cores and be electromagnets or may be replaced by permanent magnets without prejudice to the experiment.

Usually there is said to be a magnetic field of force

between the two coils or magnets. The direction of such a field is taken as that in which the north-seeking end of a compass needle would point. The direction of deflection for the stream of electrons in the large loop will then be related to this direction of the magnetic field and to the direction of the electron stream as is the thumb of one's right hand to the

FIG. 8

The relative directions of magnetic field, *F*, of the motion, *M*, of a conductor, and of the induced electron stream, *C*, in the conductor.

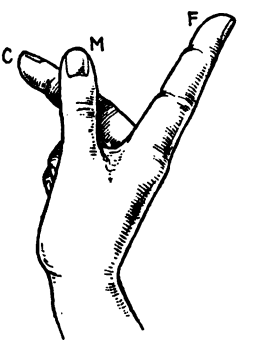


FIG. 7

The relative directions of a magnetic field, *F*, of an electron stream, *C*, and of the motion, *M*, of the stream relative to the field.

fore and center fingers, respectively, when all three digits point at right angles to each other.

In the application of this rule, as pictured in Fig. 7, it must be remembered that so far as concerns this phenomenon a stream of positive ions is equivalent to a stream of electrons in the opposite direction.

Parallel currents undergo mutual deflections at right angles to their directions. Does such deflection alter the currents? Always, for every physical action has an equal and opposite reaction. The electron streams are momentarily affected by their deflection in such a manner as to oppose the change. If the currents in two parallel wires are in such directions as to cause an attraction of the wires, then during their mutual approach the currents are momentarily decreased.

For simplicity let us concentrate our attention on a single current, choosing that of the portion of the large loop of Fig. 6 which we know is deflected across the magnetic field between the two solenoids. The wire is deflected in the direction given by the right-hand rule of Fig. 7. If there were flowing in it a stream of electrons in the opposite direction there would be a tendency to the opposite deflection. If the actual deflection which takes place is to be accompanied by a reaction, this reaction may be accomplished by the setting up of an opposing stream of electrons. Such a counter stream will result in a reduction in the net number of electrons which are being transferred along the wire. The current, therefore, is reduced momentarily, that is as long as there is a deflection of the wire.

Now suppose that the wire carries no current and that by some external means it is caused to move across the field between the two solenoids of Fig. 6. Let its direction of motion be the same as before. The original stream of electrons no longer exists but the induced stream comes momentarily into exist-

ence just as before and its direction is such as to oppose the cause inducing it.

The relations of direction of motion, direction of field, and direction of the induced stream of electrons will be identical with that pictured in Fig. 7, except that the direction of the electron stream is reversed. By using the left hand, however, as shown in Fig. 8, the directions may be represented by the same symbols as before. We may call the left-hand relations those for the induction of electronic streams and the right-hand relations those for the deflection of electronic streams.

It is this phenomenon of the induction of electronic streams which is used to such industrial advantage in the so-called "generation of electricity" for power purposes. By rotating machinery, coils of wire are kept in motion across magnetic fields and thus there are obtained streams of electrons which may be guided by wires to points where the energy of the moving electrons may be utilized.

The utilization may involve the phenomenon of the attraction of parallel streams of electrons in motors where the electron streams cause coils of wires to rotate relative to electromagnets. In many cases the utilization involves the release of the energy of the electron streams in the form of the heat and light which results from the impeded progress of the electrons through wires which offer high resistance.

# CHAPTER VIII

## THE PROOF FOR THE EXISTENCE OF AN ELECTRON

Our knowledge of the interactions of magnets dates from Gilbert, the Elizabethan physician; our knowledge of the interactions of a magnet with an electric current, or of current with current, started with Oersted in the early nineteenth century; and our knowledge of electronic structures has been almost entirely a twentieth-century development. It is natural, therefore, to say that electric currents produce magnetic effects. Magnetic properties were attributed to currents in order to explain their interactions. Today, however, we incline toward the explanation of the properties of so-called magnetic substances in terms of revolutions of the electrons within their atoms, although we do not know definitely the nature of these revolutions.

The chemical properties of atoms, which were discussed in Chapter III in connection with the periodic table, are most easily explained if we assume the planetary electrons to be located in fairly definite positions. The magnetic properties are best vizualized if we assume electrons to be rotating. The emission of light, as we shall see later, requires that the electrons shall be in rotation and that their orbits shall change under various conditions. So far no

satisfactory picture has been presented, although for the simpler atoms of hydrogen and helium there have been suggested atomic models which would have properties in agreement with those observed for these substances.

Although we are in ignorance of the exact form of the paths pursued by the electrons in atoms we are perhaps justified in assuming that rotations do occur and in explaining so-called magnetic attractions by the interactions of electrons which are moving in parallel paths. If the paths are at right angles there are no attractions. For intervening directions the attraction depends upon the components of the motions which are parallel. The idea of a component is easily grasped when one realizes that if two bodies are not going in directions exactly at right angles to each other, they must to some extent be going in the same direction, and, with equal truth, to some other extent at right angles to each other. The extent to which one body is moving in the same direction with a second is the component of the motion of the first in the direction of the second.

The magnetic attraction which occurs between electrons with components of motion in the same direction is very probably one reason why such mutually repulsive entities as electrons can form a group about an inner nucleus. The magnetic attraction may partially offset the tendencies of the electrons to pellate and may thus assist the nucleus in retaining them within atomic limits. It may also be that the protons and electrons within the nucleus are restrained from flying apart by similar attractions.

To make these attractive forces commensurable with the natural repulsions of similar electrical elements would require high speeds for the elements which are rotating and thus represent large energies. This would fit with the observed facts as to the high energies possessed by alpha and beta particles. The actual geometry of the atomic nucleus,[1] however, is far in the speculative twilight, although present scientific progress is so rapid that the whole matter might well be explained within a few years.

In dealing with the interactions of electrical currents it is usual to speak as if one current acted on the other and to neglect the reaction of the second on the first. To the acting current we attribute a magnetic field and then speak of this field as acting upon the current in which we are interested. It is in this terminology that one will find described the classical experiments which established the electron theory with which modern science starts. Throughout all the original reports one will find the idea of fields of force, not only magnetic but so-called electrostatic fields. The latter are the regions near charged bodies and the direction of the field is taken, unfortunately, as that in which a positive charge would move.

By applying magnetic and electrostatic fields of force to the streams of particles which are expelled

[1] The most recent evidence is that of C. J. Darwin (February, 1921) who worked with Professor Rutherford in the latter's experiments on the collision of alpha particles with hydrogen nuclei. The evidence seems to support the idea that an alpha particle has a shape something like a plate or disc with a diameter of $2.7 \times 10^{-13}$ cm. The evidence comes from experiments similar to those described on page 113.

from radioactive bodies, there was obtained the first information that these were streams of particles or corpuscles instead of radiations as intangible and imponderable as those of light. In a magnetic field a stream of alpha particles is deflected in the opposite direction from a stream of beta particles, and the same is true for an electrostatic field such as exists between two oppositely charged plates. The proof of the existence of electrons, however, was reached largely by the study of so-called "cathode rays."

The origin of the latter phrase is explained as follows: In the study of electrolysis, that is the conduction of electricity through liquids which was discussed in Chapter II, two terminal plates are inserted in the liquid. The positive plate was called the anode and the negative the cathode since it was assumed that electricity flowed up to one and down to the other. The terms have been retained and applied to the terminal plates in conduction through gases.

We remember also from our discussion of gases that electrons are liberated at the negative plate when there is a sufficiently severe bombardment of this plate by positive ions. If the tube containing the gas through which conduction is taking place is not too highly exhausted a relatively large number of gas molecules are present and may be ionized. On the other hand, if it is not so little exhausted that a gaseous molecule is stopped by collision before it travels a distance, representing a potential difference, sufficient to acquire the necessary energy, then the impacts of the positive ions will liberate electrons

from the cathode. These shoot off into space, repelled by the negative plate from which they are derived. Their energy comes from the battery which keeps the cathode negative, by forcing upon it electrons far in excess of its possibilities of getting rid of them. Electrons may be freed from the cathode and so made available for conduction through the tube only by the bombardment of the positive ions (or by other agencies, like ultra-violet light, which do not concern the present case).

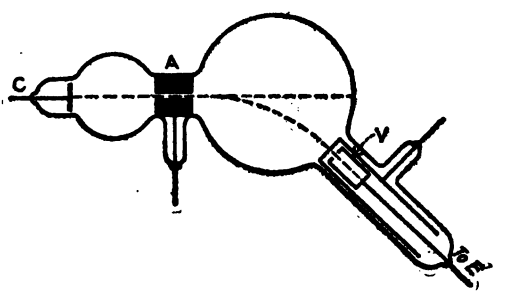


FIG. 9

Cross-section of apparatus for examination of cathode rays. The cathode stream from *C* passed through the tubular anode, *A*. It was deflected by the magnetic field into the vessel, *V*, for which an electroscope, *E*, then indicated a negative charge.

The result is a steady stream of electrons, flying from the cathode with velocities which may be almost as enormous as that of light. These constitute the "cathode rays," as they were first called. Where they impinge on the glass of the tube they cause it to phosphoresce, and thus their paths may be traced. Many of the electrons travel straight for the positive terminal, or anode. If the latter is made hollow, or perforated, many will pass straight through with al-

most no regard for its attracting excess of protons for they are going too fast to stop. The result is that a "beam" of cathode rays is available for experimental study in the space beyond the anode, as shown in Fig. 9.

Through this space the beam travels straight except as deflected, for example by magnets set outside the tube so as to establish a magnetic field at right angles to the stream. In one of the original experiments of J. J. Thomson the beam was deflected into the hollow metal vessel, *V*, shown in the figure. The direction of deflection indicated that the beam was a stream of negative particles. Further evidence came from the charge which the beam gave to the vessel *V*, for the latter was found to be negative.

You will remember, however, that it should also be possible to deflect the beam by placing above and below it oppositively charged plates. If the upper plate is made positive the stream of electrons should be attracted toward it and repelled by the lower negative plate. By subjecting the beam to this influence the effect of the magnetic field can be counteracted, provided that there is maintained a certain relation for the intensities of the electrostatic field which deflects upward and the magnetic which deflects downward. It happens that the ratio of these intensities depends only upon the velocity with which the particles in the stream are moving. By such a balancing of deflections, therefore, Thomson was able to determine the velocity of the particles. His apparatus is shown in Fig. 10.

Up to this time the electron was unknown and

electricity had been measured in other units than this natural unit. He next sought in terms of existing units to measure the charge which each particle carried. However, it was not then known how to measure this quantity directly, and the method he devised gave the relation of the charge on the particle to its mass (inertia).

He found this ratio by observing the deflection which was produced when only the electrostatic field was active. Each electron in the stream behaves

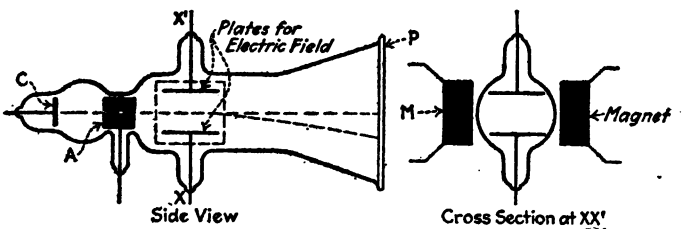


FIG. 10

Apparatus used by J. J. Thomson for determining properties of cathode rays. Electrons from *C* pass through *A* to the screen, *P*. The magnets and the plates deflect the stream up or down, depending on their respective polarities.

like a bullet shot in a horizontal line and the plate toward which it is attracted acts like the earth with its gravitational pull. The constant pull gives the particle an acceleration toward the plate just as in the case of a bullet and the earth. The acceleration, however, depends upon the charge, for it is by virtue of the charge that the particle is attracted toward the plate, and upon the mass or unwillingness to be accelerated. From the horizontal and vertical dimensions of the parabolic path which the particle pursued Thomson determined the ratio of its charge to

its mass. It was found to be about 1700 times the similar ratio for the hydrogen ion which takes part in electrolytic conduction.

An approximate value for the mass of the particle in a cathode ray was then obtained upon the assumption that the ion of hydrogen is essentially the same in mass as the hydrogen atom and that the charge of electricity which it carries is equal but opposite in kind to that of the particle under examination. Upon this assumption the mass of the unknown particle was obtained as one-seventeen-hundredth of a hydrogen atom, since its mass must be that much smaller in order to make the ratio of charge to mass correspondingly larger.

Methods for determining the unknown charge on the particle were soon devised and one by Townsend was widely used. The latter knew that not all the gas which escapes at an electrode in an electrolytic action, like that described at the end of Chapter VI, is composed of neutral uncharged molecules. Once in a million times or so a molecule may carry away a charge, the result, apparently, of hasty combination. Whether the molecule gets out into free space with one too few, or one too many, electrons is not accidental but is characteristic and depends upon the electrolyte from which the gas rises.

If the air above the electrolyte contains moisture, that is molecules of water wandering about like molecules of ordinary gas, then the charged molecules act as centers of attraction for the water molecules. The latter aggregate about the charges, forming small drops which appear as a cloud. The

natural assumption is that in such a condensation the number of droplets is equal to the number of centers about which drops can form. Townsend therefore calculated the number of drops in the cloud, measured the electrical charge involved, and thus found the charge per drop, that is the desired elemental charge.

The number of drops was obtained by calculating the amount of water in each drop and then dividing this into the total weight of the entire cloud. The latter was found by passing the cloud through tubes filled with chemicals, which took up the water, and observing their increase in weight. The volume of the drops was calculated on the basis of earlier work by Stokes who had expressed quantitatively the law for the descent under gravity of small drops. The smaller the drop the more slowly does it fall. Such drops as formed the clouds with which Townsend worked will take about half a minute to fall through an inch of air. By observing the rate of fall of the entire cloud the average size of its drops could be computed and hence their weight obtained.

To measure the total charge which the cloud carried there was used a calibrated electroscope, or electrometer, as it is called. This instrument has proved of great usefulness in most of the experiments which have led to the present state of our knowledge of electrons and radioactive substances. In simplest form it consists of a vertical metal strip to which is attached a light gold leaf. The metal strip is insulated from the protecting case through which it projects to an external knob.

If a charged body is brought in contact with the knob there is a transfer of electrons either to the knob or from it. Let us suppose the body negative. Then electrons pass to the knob and because of mutual repulsions pass down into the metal strip and its gold leaf. There their repulsions result in the deflection of the gold leaf which stands out at an angle from the vertical. When the charged body is removed some of the electrons at the bottom of the strip are repelled back to the knob and the leaf drops a little to a new and final position which it maintains except as the charge on the system is neutralized by stray ions in the air about it.

If now another charged body is brought near but not into contact with the knob two different actions are possible. If the new body is negative the electrons are again repelled into the extremities of the strip and gold leaf and there results an increased deflection. On the other hand if the new body is positive its excess of protons attracts electrons toward the knob and the number at the bottom of the system are no longer sufficient to maintain the former deflection so that the leaf falls back.

The same effect is, of course, produced if a charge is added to the gold leaf system by direct contact of the charged body with the knob. The only difficulty is that if the charge is of opposite kind to that already on the system it may neutralize that charge, allowing the leaf to drop, and instantly recharge the electroscope with the opposite kind of electricity, causing the leaf again to stand out from its support. By proper care, however, the change in deflection of

the gold leaf may be made not only to indicate the kind of charge but also to measure its amount. By such a method Townsend determined the total charge on his cloud.

The series of experiments described above were sufficient to establish the fact that cathode rays are streams of negatively charged particles, each with a charge like that of the hydrogen ion in electrolysis, and a mass about one 1700th of that ion, and also to determine in terms of the standard units the charge on individual particles. With the conclusion of this series the existence of the electron was established.

Experiments of this character are obviously complicated since they generally involve a number of necessary subsidiary experiments as well as mathematical formulation and a careful use of units. In this book we shall describe only a few. One, which deserves immediate attention, is Millikan's method for determining the value of an electron in terms of the earlier accepted units for electrical charge.

Millikan's work, extending from 1907 to 1917, was a series of ingenious experiments, each more simply direct than the preceding and adapted to giving more precise results. In one of these, instead of a cloud, he used a single drop under conditions which eliminated the properties of the drop itself and of the medium in which it was placed and gave direct indications of the electrical charge which the drop carried.

The principal features of his apparatus appear in Fig. 11. Between the two parallel plates, $M$ and $N$, a droplet was introduced by spraying oil from an

atomizer into a chamber above. Drops about one-ten-thousandth of an inch in diameter were thus formed. As these fell slowly through the chamber one would find its way through the small hole at *p* into the space between the plates. Here it was made visible as a bright speck, by a powerful stream of light, just as particles of fine dust in the air are

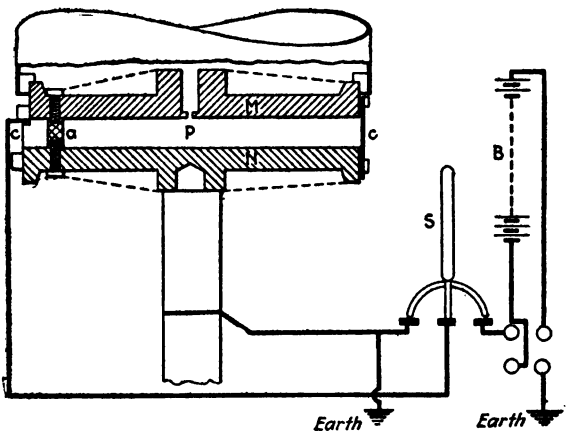


FIG. 11

Cross-section of Millikan's apparatus for measuring the elemental charge of electricity (the electron). An electrified oil drop between the plates *M* and *N* falls or rises, depending upon the electrical condition of these plates, and this is controllable by the battery, *B*, and the switch, *S*.

made visible by a transverse beam of sunlight. Its motion was observed through a small telescope and was timed by a stop watch or a chronograph.

Between the plates an electrical potential was applied by a battery, *B*, so arranged with switches, *S*, as to permit making either plate positive and the other negative. The drops acquired charges by friction as they left the atomizer. The plates, however,

were not charged until a drop was seen in the field of view of the telescope. As long as the plates remained uncharged the drop would fall slowly, about one thirtieth of an inch a second. Connecting the plates to the battery would result in a change of speed. If the charge on the drop was the same kind as that of the upper plate it would fall more rapidly, but if opposite to that of this plate it would either rise or remain practically at rest, depending upon whether or not the potential applied to the plates was sufficient to do more than neutralize the gravitational effect.

The drop was caused to rise and allowed to fall, alternately, and the times were observed. Sometimes the drop would suffer collision with some ion of the atmosphere between the plates and then because of its changed electrical condition its time of rise would be changed, but its time of fall, when the plates were uncharged, would not change. A fair supply of ions for such collisions were provided by bringing radium near the apparatus or by exposing the air between the plates to X-rays.

The drop could be caused to collide with either positive or negative ions by the following method: Suppose it was desired to add positive charges to the drop. It would be brought near the negative plate and then kept from falling by properly adjusting the potential. Then the space would be exposed to ionizing radiations from the radium. The negative ions, thus formed, would move toward the positive plate and away from the drop. All the positive ions, however, would move toward the other plate and the drop would thus be in a veritable shower of positive

ions. In this way the charge originally held by the drop could be increased or neutralized and reversed, if desired.

A change in the velocity with which the drop rose would indicate a change in the charge it carried. If there is an elemental charge there should be a definite minimum change in velocity corresponding to adding or subtracting this charge from the drop and all other charges should be small exact multiples of this minimum. On the assumption that the electrified condition of the drop is due to a certain excess or deficiency of electrons, this is what we should expect, and this is what Millikan found. His experiment constitutes a beautiful proof of the existence of a definite elemental quantity of electricity.

By a proper correlation of his quantitative data he arrived at a very exact determination of the value of this elemental charge in terms of the usual units for measuring electricity. In the Appendix we shall consider the numerical value for this important physical magnitude. For the moment, however, we quote an illustration from Millikan to relate the electron to a familiar magnitude. He says that the number of electrons which pass every second through a common 16-candle power electric-lamp filament is so large that it would take the two and a half million people in Chicago, counting at the rate of two each second, twenty thousand years of 24-hour working days to count an equivalent number.

It made no difference how the electrification was produced or the charge transferred. Millikan used thousands of drops in various media, experimenting

with drops of non-conducting substances like oil, poor conductors like glycerin, and excellent metallic conductors like mercury. He states that "in every case, without a single exception, the initial charge placed upon the drop by the frictional process, and all the dozen or more charges which resulted from the capture by the drop of a larger or smaller number of ions, were found to be exact multiples of the smallest charge caught from the air."

His experiments were a beautiful demonstration of the correctness of the concept of an electron. They "placed beyond all question the view that an electrical charge, wherever it is found, whether on an insulator or a conductor, whether in electrolytes or in metals, has a definite granular structure, and that it consists of an exact number of specks of electricity (electrons) all exactly alike, which in static phenomena are scattered over the surface of the charged body and in current phenomena are drifting along the conductor."

# CHAPTER IX

## ISOLATING A PROTON

THAT there is an elemental quantity of electricity was definitely shown by the experiments of Millikan which were described in the last chapter. His experiments are apparently the most accurate and convincing because of their simplicity. They constitute a final proof in a long series of independent investigations by various physicists. Some had experimented with cathode rays, proved that they were formed by small charged particles and found the mass and charge of the particles (electrons). Others had carried out similar investigations of the beta rays from radioactive substances, proved their granular nature, and found for their particles the same value of electrical charge. In beta rays, however, the electrons move with high velocities, very nearly that of light, and usually much higher than in cathode rays. The investigators found that while the quantity of electricity represented by an electron in a beta ray was the same as that in a cathode ray, the mass was in general much greater, that it depended upon the velocity and was enormously greater for velocities nearly that of light.[1]

The quantity of electricity which constitutes the

[1] *Cf.* p. 205 of the Appendix.

elemental charge had also been determined from a knowledge of electrolytic phenomena and by deduction from certain phenomena of radiation. It was determined also from measurements of alpha rays by experimental methods similar to those used for cathode rays. In the case of gaseous ions the elemental charge had been determined by variations of the "cloud" method which was described in the preceding chapter.

The net result of all these experiments has been the common acceptance of the idea of a definite elemental quantity of electricity, and its identification with the electron which appears in cathode rays and beta rays. For some years, however, nothing very definite was known about the complement of the electron, the equivalent positive charge of electricity[1] which we are calling the proton. At first all that could be said was that an atom consisted of electrons which could be isolated and a nucleus which must have a positive charge equal to the negative charge represented by the electrons which surrounded it.

Knowledge of the elemental positive charge has come partly from a study of radioactivity and partly from a study of conduction through gases. The earlier determinations of the elemental charge by the cloud method had employed the ions of conducting gases, sweeping them aside from their normal course by highly charged plates and thus collecting similar ions for measurement. Determinations of the number of ions in these experiments were based upon the phenomenon discovered by C. T. R. Wilson that

[1] Which is usually known as the "positive electron."

ions act as centers for the condensation of water vapor.

This phenomenon Wilson used also to obtain some interesting pictures of the progress of swiftly-moving charged particles. When an electron is shot through a gas, in which there is a large amount of water vapor, its progress is recognizable by small drops, formed about the ions which result from its collisions with the molecules of the gas. One of Wilson's pictures of the path of a high-speed electron, a beta particle, is reproduced in Fig. 12. Drops due to several ionizing particles are seen but those produced by the particular particle under consideration appear as a straight line lengthwise through the center of the picture. This beta particle moved so rapidly through the atomic systems of the gas and the free spaces between that only rarely was it long enough in the neighborhood of any particular electron to displace it permanently from its colleagues in an atom. It ionized only about one of every 10,000 gas molecules through whose systems it passed.

In Fig. 13, on the other hand, appear the paths of some alpha particles from radium. Although these heavier particles ionized millions of gas molecules in each centimeter of their progress they were rarely deflected from straight-line paths. In two cases in this figure there may be seen sharp changes in their directions. These occurred near the ends of their paths, when their energies were much reduced by their previous activities, and are believed to represent collisions with the nuclei of gas molecules. In the earlier parts of their paths there were

undoubtedly some similar collisions but the number was relatively small and the momenta of the alpha particles were such that they suffered inappreciable deflections. Probably they drove before them the molecules of gas with whose nuclei they had head-on collisions much as does the cue ball in a well-played "follow shot" in billiards. The smallness of the alpha particle and of the nuclei of atoms, in general, explains, however, the infrequency of deflection in those later portions of their paths when their abnormal energy is almost entirely absorbed and they are becoming as the other atomic systems through which they pass.

As early as 1911 Rutherford applied this phenomenon, of the deflection of the positive alpha particle by the positive nucleus of an atom, to a quantitative determination of the charge on the nucleus of various types of atoms. That on the alpha particle was, of course, known from previous work as equal in amount but complementary in kind to the charge of two electrons. He computed the chance that an alpha particle would suffer a given deflection by being shot through thin sheets of foil of gold and other metals. The method of the experiment involves a principle which is widely applied in the study of radioactivity.

The method is that of counting scintillations. When alpha particles strike a screen of zinc sulphide, for example, they give rise to bright specks of light. Each particle apparently sets into vibration the electronic systems of several atoms and these vibrations the eye recognizes as light. The phenomenon is

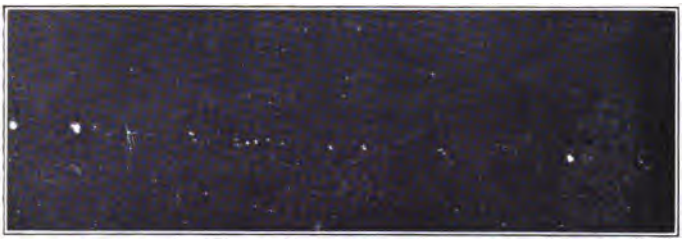

FIG. 12. The trails of beta particles (electrons), moving swiftly through humid air, as shown by drops of water which formed about the ions produced by the impacts of the electrons. (Reproduced from original memoir of C. T. R. Wilson.)

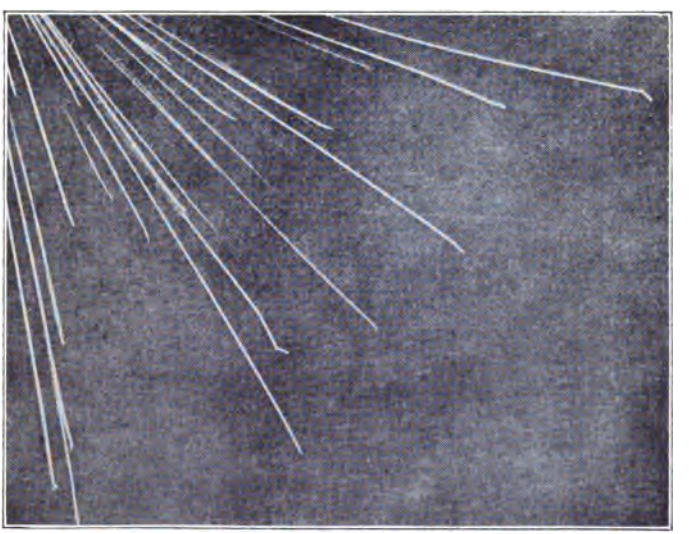

FIG. 13. The trails of alpha particles as shown by the condensation of water vapor on the ions which were formed by their impacts. (Original in scientific memoir of C. T. R. Wilson.)

PLATE I

similar to that involved in the recognition of the impact of cathode rays by the fluorescence of the glass of cathode ray tubes.

The particular experiment involved finding what fraction of a thousand alpha particles, which were shot through a sheet of foil, produced scintillations at a location on the screen corresponding to the given angle of deflection. It was determined by calculation based on this experimental method that the number of elemental charges on the nucleus of an atom is approximately equal to half its atomic weight.

This was the first determination of atomic numbers. Although the method is not capable of very exact indications and although the values obtained are necessarily only indicative, the experiments implied a definite granular structure to positive electricity such that nuclei of different atomic systems differ by whole numbers of elemental positive charges. It gave no hope of isolating the elemental positive charge (proton).

Further indications and very exact quantitative results on atomic numbers were obtained about three years later by Moseley. His method, however, involved X-rays and will be discussed in the following chapter.

The next evidence as to the proton came from experiments on so-called positive rays. In the conduction of electricity through gases, as we have seen, the term "cathode rays" was applied to the stream of electrons which proceeds away from the negative electrode. In the preceding chapter we have seen

how experimenters arranged a hollow anode so that a pencil of these rays might pass beyond the anode and be subject to examination or use. In much the same way the term "positive rays" has been applied to the positive gaseous ions which are urged toward the cathode. By making the latter a hollow cylinder these positive ions may be passed into the space beyond.

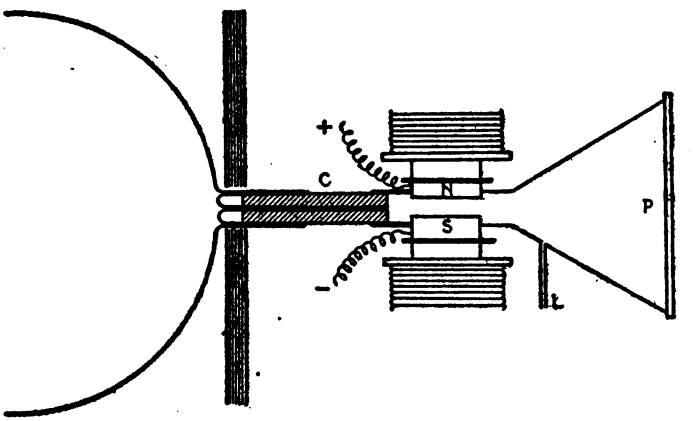


FIG. 14

Cross-section of apparatus for positive ray analysis. (Illustrating method of J. J. Thomson.) The stream of positive ions passed through the hollow tubular cathode, *C*, to the photographic plate, *P*. It was deflected by an electric field (due to a battery connected at +, —) and by an electromagnet, *N-S*, and thus acted to trace a parabolic curve on the plate. Tube *L* connected to the vacuum pump.

If the cathode is a long cylinder of small cross section like that of Fig. 14, there is relatively little diffusion or mixing of the gases of the two parts of the vessel. For this reason the gas pressure within the conducting portion of the tube may be main-

tained at the proper value to secure the optimum density of gas molecules for the formation of ions and the remainder of the enclosed system may be practically a vacuum and thus contain few molecules to impede the progress of the ions which constitute the positive rays. At the end of this second portion of the tube a photographic plate, *P*, permits a record of the stream, for each ion, as it strikes, disturbs the electronic composition of the neighboring atoms of the plate, much as does light in ordinary photography.

In one sense, of course, alpha rays are positive rays. They are helium ions, identical with helium atoms which have lost two electrons each. They differ from helium positive-rays, which would be formed if the tube of Fig. 14 contained helium in its conducting chamber, in their origin, for alpha rays arise from radioactive disturbances. They differ also in velocity, at least in the early portion of their progress, for they may have original velocities as high as a tenth that of light. In conduction through gases no such high velocities are attainable. They may differ in the number of electrons which are lost, since ionizing impacts in a conducting gas usually remove only a single electron from such stable structures as the inert atoms, although they frequently remove two from substances like nitrogen, or more than two from metallic atoms like those of mercury vapor.

It was this high velocity and hence high penetration of alpha particles which permitted Rutherford to make his classical demonstration of the fact that

alpha particles are really helium ions. He used a very thin-walled tube like that shown at *A* in Fig. 15. He first showed that there was no connection between *A* and the larger tube, *B*, by filling *A* with helium and observing that there was none of the spectroscopic characteristics of helium gas when a current passed between the electrodes of *C*. Next

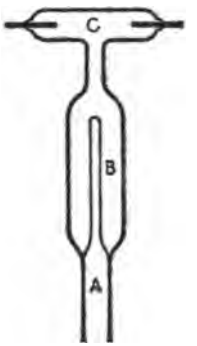


FIG. 15

Cross-section of Rutherford's apparatus for showing that alpha particles are helium. An electric current through *C* gives a radiation characteristic of the substance in *B*. When radium emanation was placed in *A*, the spectrum of the radiation from *C* showed traces of helium.

he removed the helium from *A* and substituted radium emanation. After a few hours the spectroscope showed that helium was present in the discharge path between the electrodes of *C*. The only way helium could get into *B* and *C* was by being identical with the alpha particles which are emitted by radium emanation. The high velocities of these particles are sufficient to carry them through the atomic systems of the glass walls just as well as through less closely packed atomic systems of gases.

The velocities of the positive ions from a gas which is conducting electricity are insufficient, as we have said, to produce some of the effects of the swift alpha particles. The ions do, however, affect photographic plates and may, therefore, be easily studied. Suppose, for a moment, that all the ions which form the positive rays, from such a tube as that of Fig. 14, are of the same mass. They will differ in velocity because they have been formed at different points in the tube, have fallen through different potentials

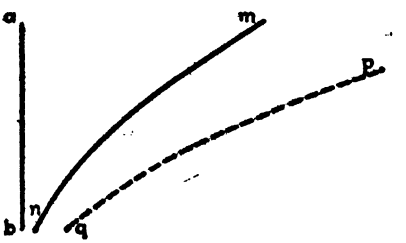


FIG. 16

Parabolas formed on the plate, *P*, of Figure 14.

and have suffered different collisions. Because the beam of positive rays is not homogeneous in velocity the various particles which compose it will suffer different deflections under the influence of a field of force, whether magnetic or electrostatic.

If a magnetic system is so placed as to deflect the particles upward some of them will be deflected but little, others more and the result will be a line of points on the photographic plate. Such a line is represented as *ab* in Fig. 16. If, now, an electrostatic field is established which produces a deflection at right angles to that of the magnetic field, each

component particle of the beam will be deflected, say to the right, by an amount which depends upon its velocity. The result is a series of spots which lie, as shown at *mn* of the figure, on a portion of a parabola.

For positive ions of some different mass there will be formed on the photographic plate a different parabolic curve, says *pq*. From the dimensions of these parabolas there may be calculated, as was first done by J. J. Thomson, the ratio of the masses of the types of particles which register these curves. If the tube from which the positive rays are derived contains a mixture of gases the atomic (or molecular) weights of the various particles may be derived from the various traces on the photographic plate. If, however, the particles differ not only in their masses but also in the charges which they acquire by ionization, then the analysis becomes more complicated or even impossible. Two particles, one having twice the mass of the other, and carrying twice the charge, will give the same trace on the plate for the method separates particles only when they differ in their ratios of mass to charge.

In one of Thomson's experiments he studied atmospheric air, which contains in addition to nitrogen and oxygen small amounts of inert gases like neon and argon. From the tap-grease which was used to seal the valves leading to the vacuum pump there was added to this mixture traces of carbon dioxide and carbon. In addition, since mercury was used in the pump, there was a trace of mercury vapor. In the photograph of the deflected positive rays from

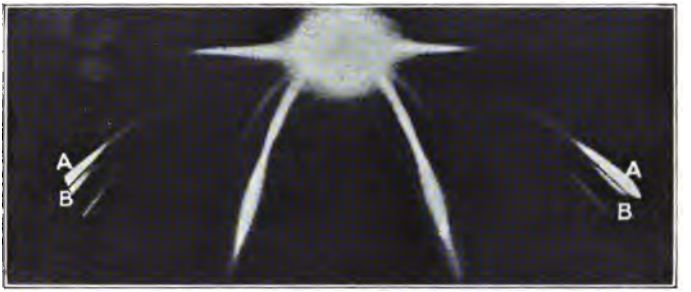


FIG. 17. Parabolas obtained in positive ray analysis by J. J. Thomson. Neon gave two parabolas, *A* and *B*. (A retouched photograph of the illustration in the original memoir.)

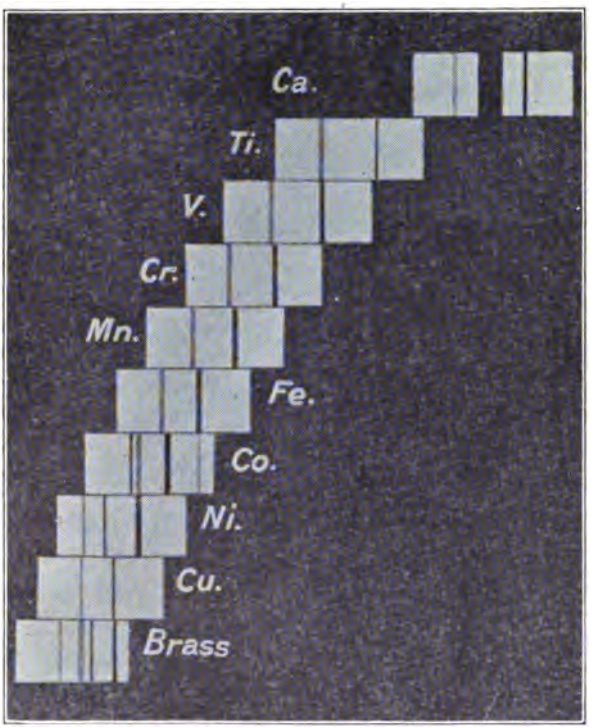


FIG. 24. Moseley's photographs of the X-ray spectra of various metallic anti-cathodes. The different photographs are placed approximately in register in the figure.

PLATE II

this mixture of gases and vapors Thomson recognized molecules of nitrogen and carbon dioxide which had lost one electron; atoms of nitrogen, oxygen, carbon, neon, and argon which had lost one electron each; and atoms of mercury which had lost respectively one, two and three electrons.

The appearance of the curve for neon was much like that of Fig. 17, which is not an exact copy of the original photograph but was retouched to exaggerate slightly a peculiarity of the original. Apparently there are two curves, *A* and *B*, close together. From the more prominent curve, *A*, the mass of the particle was found to be 20 and from the other 22. In this way the isotope of neon was discovered.

The most recent and reliable series of analyses of the so-called chemical elements by the method of positive rays is that of F. W. Aston. He discovered isotopes of other chemical substances, like chlorine, which were formerly supposed to be elementary. In his method the electrostatic and magnetic fields are arranged so that their deflections occur subsequent to each other as the ray progresses instead of simultaneously. The precision of his results is remarkable as compared to other positive ray analyses for the probable error of his determinations is only about one-tenth of one percent.

Our present interest in his work is due to the fact that he not only isolated the proton, that is the positive hydrogen ion—for Thomson had done this in his analysis—but he made for its mass a very precise measurement. Aston compared the mass of the pro-

ton with that of the hydrogen molecule and the mass of the latter with that of the helium atom.

You will remember that the ordinary chemical determinations by weighing had resulted in atomic weights of 1.008 for the hydrogen atom, twice as much for the diatomic hydrogen molecule, and 4.00 for the helium atom. Aston's determinations are corroborative and indicate definitely that the mass of the proton, when free or when constituting the nucleus of a hydrogen atom, is eight-tenths of a per-cent greater than when it is combined with electrons in a nucleus.

His method was as follows: If the photographic plate is exposed successively to impacts of ions of a given mass and to ions of twice that mass which, however, are deflected by an electrical field of twice the intensity, then the two traces should be coincident and indistinguishable. If, on the other hand, the field is not quite doubled the line for the atoms of double mass will lie very near but not coincident with that for the atoms of single mass. Similarly by taking a third exposure for the atoms of double mass, but using for deflection an electrostatic field as much greater as it had formerly been less, another line is obtained equally spaced on the other side of that recorded by the atoms of single mass.

In applying this method he exposed a plate to positive rays containing molecules of hydrogen which had been ionized by the loss of an electron. Then using first slightly more than double the potential on the deflecting plates and second an equal amount less than this double potential, he obtained two

records for helium ions. These are shown in Fig. 18A which is a drawing based on the photographs of his original paper. It is evident that the trace for the hydrogen molecule is not midway between these bracketing lines as it would be if the mass of $H_2$ were just half that of He. On the other hand from Fig. 18B it is seen that the line for molecular ions, $H_2$, is equally bracketed by the lines of the atomic ions, $H_1$.

FIG. 18A

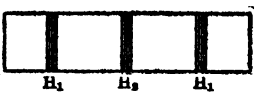


FIG. 18B

Drawing based on the positive ray photographs by means of which Aston compared the atomic weight of the hydrogen molecule with that of the helium molecule (Figure A), and of the hydrogen atom with that of the hydrogen molecule (Figure B).

Since the work of Aston it becomes possible to speak definitely of an element of positive electricity, complementary to the electron, and when isolated equivalent in mass to the hydrogen atom. When the proton is not isolated it is apparently secreted in the alpha particles which are known constituents of the nuclei of the radioactive elements and by inference constituents of all others. In one case, that of nitrogen,[1] there seems to be direct evidence that the proton is a constituent of the atomic nucleus. The evidence was obtained during 1918 by Ruther-

[1] In a letter to the Editor of *Nature*, March, 1921, Rutherford announced similar phenomena for boron, fluorine, sodium, aluminum and phosphorus, and said, "While we have no experimental evidence of the nature of these particles, except in the case of nitrogen, it seems likely that the particles are in reality H atoms."

ford but he was in doubt as to whether it indicated a single proton or a particle composed of two such elements.

The isolated positive particles of which he obtained evidence were produced from nitrogen by bombarding its molecules with alpha particles. As it happens alpha particles have very definite ranges through which they will penetrate before losing their ability to produce scintillations. For each radioactive substance there is a thickness of normal atmosphere which its alpha rays can penetrate. For those from radium the range is 3.5 centimeters but for radium C it is twice as much. However, if the screen whereby scintillations are to be observed is placed more than seven centimeters from radium C there are still occasional scintillations. These have been shown to be due to ions produced and driven forward by the impacts of the alpha particles with atoms of the gas through which they pass. For example, if the atmosphere is hydrogen scintillations are observable at a distance from the source effectively four times as great.

According to Rutherford about one time in a hundred thousand an alpha particle will come so near to hitting the nucleus of a hydrogen atom as to propel it along the line of its own motion. His calculations show that smaller increases in range should result if the alpha particles are projected into other gases than hydrogen; thus for oxygen and nitrogen the range in centimeters should be extended only from 7 to 7.8 and 9 respectively. From air, therefore, there should be produced a few long-range

particles which should not however be visible beyond about 9 centimeters.

He found that the actual number of scintillations was in excess of that expected and that the range was practically that of the hydrogen particles. When pure nitrogen was substituted for air there was an increase of twenty-five percent in the number. Since, by volume, air is four-fifths nitrogen we should expect the effect in pure nitrogen to be five-fourths as large if it were solely a phenomenon of nitrogen. Rutherford showed conclusively that it was such; but he was unable, with the small number of long-range particles which were formed from the nitrogen, to determine whether their atomic mass was 1 or 2. As he said, "From the results so far obtained it is difficult to avoid the conclusion that the long-range atoms arising from collision of alpha particles with nitrogen atoms are not nitrogen atoms but probably atoms of hydrogen, or atoms of mass 2. If this be the case we must conclude that the nitrogen atom is disintegrated under the intense forces developed in a close collision with a swift alpha particle and that the hydrogen atoms which are liberated formed a constituent part of the nitrogen nucleus."

What becomes of the rest of the nitrogen nucleus? Nobody knows. The determination of the fact of its disintegration was an experiment requiring a delicacy of operation, an imagination, and a persistence of which only a master is capable. If he failed to detect the by-product of the disintegration it must await other experiments in which alpha particles of

greater energy shall be used for bombardment. The guess may be made, however, that the nitrogen atom is disrupted into two long-range particles (protons), three alpha particles, and an electron.[1]

With the experiments of Thomson, Aston, Rutherford, and others we may, however, take as definitely settled a granular structure for positive electricity and an atomic nucleus composed of these grains in close combination with their complementary electrons.

[1] Rutherford, apparently, is inclined to believe that nuclei involve particles of mass 3 and charge 2 (that is, of three protons and one electron) which would form normal atoms, isotopic with helium (mass 4, nuclear charge 2). In this connection the work of W. D. Harkins is specially important. The latter has shown that for all known atoms (excepting atoms with only a transitory existence, such as those produced by Rutherford) the atomic mass and atomic number can be explained on the basis of a nuclear structure in which there are never less than half as many electrons as protons. For atoms of even atomic number, the ratio is exactly ½. Such atoms as analyses have shown are most abundant in meteorites and in the surface of the earth. They are apparently the stable atomic forms. Atoms of uneven atomic number have slightly higher ratios for the numbers of electrons and protons in the nucleus. Rutherford's nuclear corpuscles would have a ratio of 1/3, which is not in conformity with the other evidence. Until further evidence is presented the general reader may, perhaps, be safe in assuming atomic structures to be composed of alpha particles and in some cases to include extra protons.

# CHAPTER X

## X-RAYS AND ATOMIC NUMBERS

EXPERIMENTS on the scattering of alpha rays by their collisions with the nuclei of atoms in passing through thin sheets of metal early indicated an approximate relationship of nuclear charge to atomic weight of one to two. The exact determination, however, of the excess of protons in the nucleus of each type of atomic system was the result of work by Moseley and others who applied and extended his methods. To understand the experiments we must consider X-ray phenomena and the construction of crystals.

X-rays, or Roentgen rays as they were once called after their discoverer, arise from the impacts of a stream of swiftly moving electrons with ordinary matter, as, for example, with a plate of platinum. From the atoms which are struck by the electrons there proceeds a radiation which we now know to be identical with visible light except for the frequencies which are involved.

Heat rays, light, ultra-violet rays, X-rays, the gamma rays which have been mentioned as sometimes accompanying electron streams from radioactive substances, and the Hertzian rays used in radio-communication are all radiations of the same

character except for differences in the frequency of the vibrations from which they originate. Except for heat rays, which are believed to be due to motions of atomic systems, and except for Hertzian waves which are due to the surges back and forth of electrons in wire systems which are conducting alternating currents, all other radiations are due to vibrations of the electrical elements within atomic systems.

Vibration and oscillation are synonymous terms. Both imply that a body moves back and forth through an equilibrium position. The farther it moves from this position the greater is its tendency to return. A simple case of oscillation is that of the pendulum bob of a clock. We start it by swinging it aside from its equilibrium position and thus lifting it further from the earth. The tractation of earth and bob then results in a motion of the bob toward its unstressed position. As it swings back it moves faster and faster. When it reaches the bottom of its swing it has an energy (kinetic) which is equal to that contributed in raising it, except, of course, for subtractions by friction with the air. By virtue of this kinetic energy it continues in motion. It can rise, however, only to the height of its original separation in the opposition direction. At any greater height it would have greater potentialities of energy. It rises, therefore, until the kinetic energy which is associated with it in the equilibrium position is converted into potential energy. At this point it pauses and reverses its motion. The time required for one complete trip, that is the interval between two suc-

cessive motions in the same direction through the same point of its path, is called the period of its oscillation. The number of periods per second is the frequency.

Oscillations in general are not restricted to a

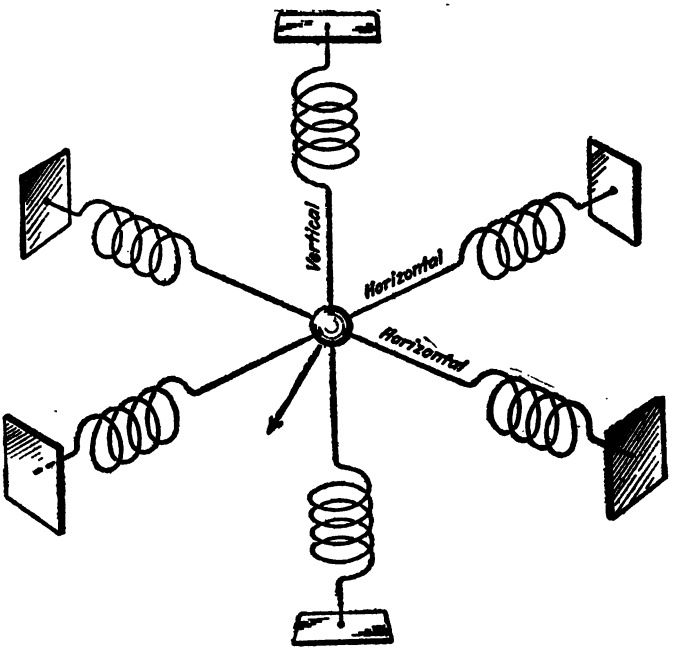


Fig. 19

Illustrating oscillations due to three restoring forces.

linear path as in this simple case where there is but a single restoring force, namely that of gravitation. Suppose, for example, that a body is constrained by forces which have components at right angles in the three directions represented by the springs of Fig. 19. If it is displaced from its equilibrium point in the

direction of the arrow all three forces will be active in its restoration and it will execute the most general type of vibration. Its frequency, which is still defined as above, depends upon the inertia of the body and the nature of the restoring forces.

In the case of molar bodies, like the pendulum of the preceding illustration, there is always a gradual dissipation of energy from the vibrating system to surrounding systems. Energy is given to the adjacent molecules of the air and by them passed on to more distant molecules. If the frequency of a vibrating mechanical system is within a certain range the vibratory motions of the air molecules may set up vibrations within the human ear which are recognized as sound of a definite pitch or vibration-frequency. Above 20,000 vibrations per second, however, the vibrations are usually inaudible for the human ear is but little sensitive outside the important frequency range of the human voice which extends from about 200 to about 5000.

Between the vibrations of molar bodies, which are observed as sound, and those of electrons within atomic structures, which are observed as light, there are several important differences. In one case the vibrating systems are aggregates of molecules and in the other discrete electrons. The restoring forces are usually due to elasticity in the case of sources of sound, and hence to intermolecular forces, but for light they are intra-atomic. The medium by which energy is transmitted from the vibrating source is molecular in one case; in the other it is at best a mere postulate, as to which more shall be

said later. The frequencies involved in sound are expressed in hundreds or thousands, while those for light are expressed in millions of millions, extending from 375 million million at the red end of the visible spectrum to 750 million million at the violet end.

The difference, however, which is most incomprehensible is that involved in the phenomena of absorption and emission of energy. When a violin string is set into vibration the energy with which it starts depends upon what energy was contributed to it in producing its initial displacement. As the string is continuously displaced there is added continuously the energy with which it shall engage in vibration. In its subsequent vibration this energy is continuously dissipated in truly infinitesimal amounts to the surrounding molecules. Both the absorption and the emission of energy are conceived as continuous phenomena, just as if there was a flow of a fluid energy which is infinitely divisible.

There is no such phenomenon as occurs in our money economy where human energy is conceived to be expended in quantities adequately represented by monetary units. Our stored energy grows by dollars or by pennies but the energy of the system we are considering increases or decreases continuously by amounts which are infinitely small parts of any of our usual units for energy.

In the case of electronic oscillators, on the other hand, there is evidence that they emit energy only in definite quantities the values of which depend upon the frequencies of their oscillations. Whether or not the operation of absorbing energy also takes

place discontinuously by similar units is still debatable and awaits further evidence. It may be that the electronic systems can absorb continuously in infinitesimal amounts but can emit only discontinuously in definite *"quanta,"* just as warlike nations may tax the tiny energies of their citizens to expend in dreadnoughts.

Unlike the vibrating systems of mechanics, whether actual or theoretical, the vibrating systems of the electrons within an atom do not radiate energy continuously but emit it in definite quanta. According to the present accepted picture the electrons may vibrate in orbits without loss of energy to surrounding systems. (This in itself is an argument against an all-embracing ethereal medium, for if it was capable of absorbing energy at all from a vibrating electron we should expect it to do so continuously.) When, however, there is a change in the orbital motion of an electron, then a quantum of energy is shot out. This quantum travels with the enormous velocity of 30,000 million centimeters a second, that is with the velocity of light.

The quantum itself is not a unit of energy but rather a specific amount. It is specific for any given frequency of vibration and in terms of the ordinary unit of energy is numerically equal to the product of the frequency by a fixed number, known from the originator of the "quantum theory" as "Planck's constant."

For any type of atomic system there appears to be a fairly large number, for example nearer to a hundred than to ten, of possible orbits for the planet-

ary electrons. Radiation occurs when an electron passes from a less stable to a more stable orbit. By interactions with other atomic systems, if they are in violent motion, or with swiftly moving electrons, a planetary electron may be displaced into a less stable orbit. During its return energy is radiated.

Violent interactions give rise to higher frequencies than do those which can contribute less energy. The gamma rays from radioactive substances and the X-rays which arise from impacts of swiftly moving electrons with atomic systems have the highest frequencies so far observed.

As to their relations of energy and frequencies more will be said later after considering the physical means for the production of X-rays. The latter may always be produced when a stream of electrons impinges on a plate, provided that the individual electrons have sufficient kinetic energy. In the original X-ray tube the electrons were obtained in the form of a cathode stream which arose from the cathode as the result of its bombardment by positive ions. The modern X-ray tube avoids the difficulty of control which is inherent in the use of a gaseous conductor and obtains the cathode stream by thermionically emitting electrons in a manner similar to that described for another vacuum tube device in Chapter VII.

The Coolidge X-ray tube, in which this principle is applied, is shown in Fig. 20. A spiral tungsten wire, *C*, serves as the cathode and is heated by passing through it a current from a battery. The anode, *A*, is a massive block of tungsten. The anode is

maintained positive with respect to the cathode by a source of very high potential. There is thus drawn across the intervening vacuum a stream of swiftly moving electrons which are further encouraged to focus upon the anode by enclosing the cathode in a tube of molybdenum, shown in cross section at *M*.

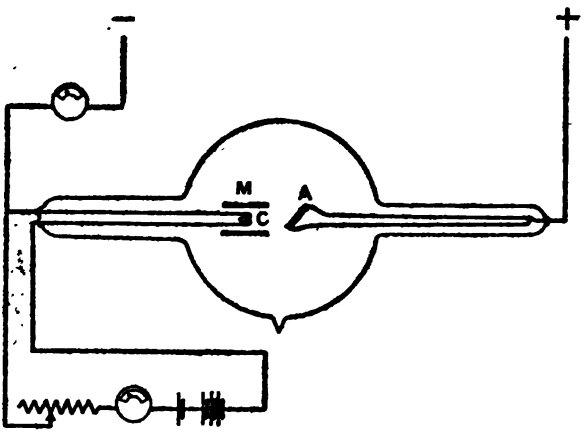


FIG. 20

Cross-section of Coolidge X-ray tube. Electrons, thermionically emitted from the cathode, *C*, are drawn across the highly evacuated space to the anti-cathode, *A*, from which X-rays arise. High voltage is applied between + and —.

The electrons of this stream violently displace from their orbits some of the electrons of the atoms upon which they fall. The bombardment apparently affects not only electrons more or less loosely held in the outer shells of the atoms—those which account for valence and ionization—but affects also electrons in the inner shells. These are displaced to new orbits from which they return to their original ones. The return is accompanied by an emission

of energy. Because these inner electrons are closely bound by the nucleus the restoring forces are large and the frequencies high, in much the same way that tightening a violin string increases the pitch of the note.

For X-rays the frequency may be twenty thousand times that of visible light, which is apparently produced by electrons further from the nucleus. On the other hand, even higher frequencies are obtained when the displacement of an electron is caused by the ejection of a beta particle from the nucleus itself. For gamma rays which arise in this way the frequencies are ten to a hundred times as high as for X-rays.

The emission and absorption of X-rays are complementary phenomena. As just stated, their emission results from the displacement of electrons by foreign electrons which violently intrude into the inner circles of the atom. When, in turn, these X-rays impinge upon atoms they eject electrons and disturb the quiet orbital motions of the inner circles. Two different phenomena are, therefore, involved when a body is exposed to X-rays, first, the ionization of some of its atoms, a phenomenon which will be discussed later in connection with other cases of ionization by radiant energy, and, second, the production of orbital changes which are of the same general character as those occurring in the atoms of the anode from which the rays arose.

The second phenomenon is one of re-radiation. The electrons of atoms which are exposed to X-rays are displaced from their normal orbits and in their

return they radiate energy. The X-rays which arise from a body exposed to X-rays are so-called secondary X-rays. The re-radiation may involve X-rays different from those incident upon the body. Some of the re-radiation will be of the same character as the original X-rays which are then said to be "scattered" by the body.

The last term is well chosen, since orderly reflection, to which we are accustomed in the case of polished mirrors and light rays, does not occur. Such reflection is possible only if the surface irregularities of the reflecting body are negligible in comparison to "the wave length," so-called, of the incident radiation. By wave length is meant the distance which radiant energy travels during each period of the vibrating source. For X-rays this distance is just about half the diameter of an ordinary diatomic molecule. No surface, therefore, can be smooth to X-rays and reflecting in the ordinary sense. For this reason the re-radiation of X-rays is usually irregular and disorderly.

It was pointed out, however, by Laue in 1912 that X-rays would be reflected in an orderly manner by the regularly spaced molecules of crystals, and further that by this means the wave length of various X-rays could be determined, provided that the distances between the molecules of the crystal were known. The experimental method was perfected shortly after by W. L. and W. H. Bragg.

The principle involved may be explained by the following analogy: Imagine the points in Fig. 21 to represent widely separated gymnasts who are to

perform identical sequences of motions at the orders or counts of a distant captain, *C*. Because the energy vocally emitted by the captain takes a finite time to travel to the gymnasts each receives the order an instant later than his next neighbor who is nearer the source. Therefore, they do not perform in step.

Suppose that each gymnast counts aloud as he executes the characteristic motions. There will be some point, as *X*, where an auditor would hear the counting of all as if they were actually counting in unison. This point must be so located that the time

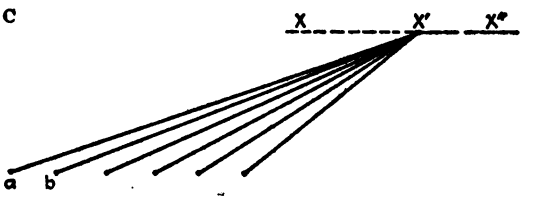


FIG. 21

Diagram to show the principles involved in the spectral analysis of X-rays by a crystal grating.

required for the sound to travel over the path $aX$ is greater than that for the path $bX$ by just the amount of time which gymnast *b* is behind gymnast *a* in his counting. On either side of *X* the auditor will receive a jumble of unintelligible and interfering sounds. At *X*, however, the sounds reenforce each other. If the gymnasts are mechanically perfect in their tasks and in their rhythm the point *X* will be sharply defined by absolute silence on either side of it. Such precision is attainable in the case of electronic gymnasts.

There will be other points also, like $X'$ and $X''$,

where there will be similar sharp maxima of re-radiated energy. The first of these will be the point where the counts heard from $a$ are one whole series behind those of $b$. Under these conditions the distance $aX'$ is a whole wave length greater than the distance $bX'$.

The actual location of these points depends upon the wave length of the radiant energy and upon the

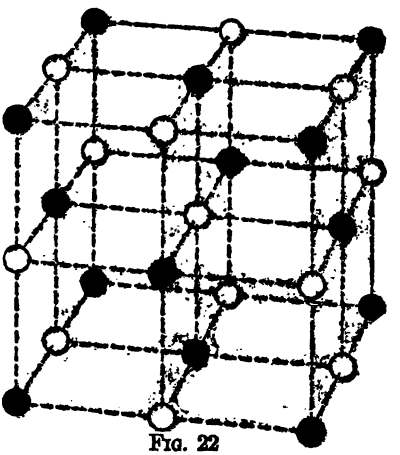

FIG. 22

Representation of a cubic crystal. If the crystal is that of common salt, sodium atoms are as represented by black circles and the chlorine atoms by light circles.

spacing of the re-radiating centers. If the latter is known the wave length may be determined. Now in crystals of certain types, namely cubic, only certain relatively simple arrangements of the molecules are possible. For example, Fig. 22 shows the simple arrangement for NaCl and similar substances. The molecules, however, are diatomic and the crystal structure is built primarily with reference to the

atoms, as we would expect from our knowledge of the opposite valence of sodium and chlorine. Adjacent to each atom of sodium is one of chlorine. The black circles in the diagram represent the sodium atoms and the other circles the chlorine atoms.

Each atom of each kind must be shared by eight small contiguous cubes, which are indicated by dotted lines. However, each small cube has associated with it four atoms of each kind. We are, therefore, correct in assigning to each small cube of a rock-salt crystal four-eighths of the mass of each kind of atom. From a knowledge of the mass of each type of atom and from the measured mass and volume of such crystals very accurate data are made available as to the dimensions of these small cubes.

Measurements of the tiny wave lengths involved in X-rays are, therefore, made possible by the use of crystals for which the dimensions of the "lattices" are known. The frequencies corresponding are then obtainable by simple arithmetic.

In such measurements the crystal is merely a portion of the instrument and there is no further concern with the physical mechanism whereby it operates. Such was the use to which Moseley put crystals in his famous investigations of 1914 before his life was sacrificed to a World War. He used the crystal grating which we have described above for the determination of the *characteristic* X-ray frequencies of various substances. The oscillators of the crystal will respond to radiations of a wide range of X-ray frequencies and re-radiate the same frequency as that with which they are excited.

Substances, however, which give rise to primary X-rays, instead of secondary, that is those which are bombarded by electrons, emit rays which have frequencies characteristic of their atomic structure. Each type of atom emits a characteristic group of X-rays. For example, when silver is used as the anti-cathode of an X-ray tube the point $X'$ of Fig. 21 appears not as a single point but as two near-by points, for two slightly different frequencies of X-rays are simultaneously emitted.

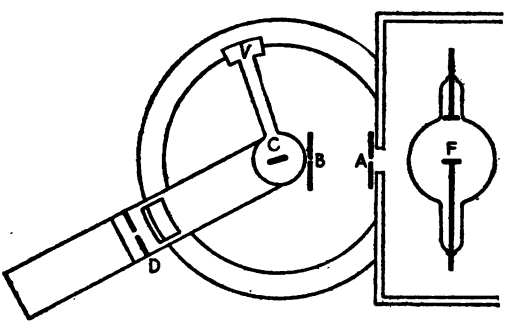


FIG. 23

Cross-section of an X-ray spectrometer. X-rays from the anti-cathode, $F$, pass to a crystal grating, $C$. The spectrum there formed is detected by a photographic plate, mounted beyond the screen, $D$.

In the examination of X-rays by means of a crystal, instead of using a point source as in Fig. 21, a narrow line source is used. To obtain such a source the X-rays from the tube are cut off by lead plates in which there are slits, shown in cross section at $A$ and $B$ in Fig. 23. A narrow rectangular beam is thus allowed to fall on the crystal $C$ of this figure. The crystal may be rotated, as may also the tube marked $D$. The re-radiated beam traverses this tube,

passes through another slit in a lead plate and falls upon a photographic plate.

Moseley took photographs successively of the X-radiation from various types of anti-cathodes. Some of these are reproduced in Fig. 24 (Plate II, opposite p. 108).

A series of similar photographs taken by Siegbahn are reproduced in Fig. 25. (Plate III.) Consider the left-hand series. As the substance from which the rays are emitted is changed from arsenic (As) to selenium (Se), or from rubidium (Rb) to strontium (Sr), there occurs the same shift in the spectrum which is of common characteristic form for all the elements.

This particular spectrum is that of the K type of X-rays. Of the different types more will be said later. For the present it may be noted that they differ in their origin, and that the K type is excited only by more swiftly moving electrons than will give rise to the L type. Characteristic spectra of the L type are shown on the right-hand side of Fig. 25.

For both types there was found a simple relationship between the frequencies of the characteristic radiations of a large number of elements. The frequencies progressed according to a simple rule as successive elements in the periodic table were examined. When the elements were arranged in order of their characteristic frequencies it was found that each was obtainable from its predecessor by simple addition. Apparently each element of the periodic series differs from the next lower by the addition of a definite amount of electricity which is accom-

panied by an increase in frequency of the characteristic radiation. It is the nuclear charge which increases and thus gives rise to greater restoring forces and more rapid vibrations when the inner electrons are displaced.

Moseley's discovery of a simple numerical relationship between characteristic frequencies did not involve measurements on all the known elements. Below sodium, for example, there are ten elements for which no X-ray spectra have yet been obtained. The inert elements also must of necessity be omitted. Thus you will notice that krypton (atomic number 36) is omitted in Fig. 25. His work and conclusions, however, have been corroborated by many other tests and may be considered the first definite proof of the structure of the atomic nucleus by grains of positive electricity (protons).

Part of the corroboration has come from measurements on the characteristic absorption which elements show for X-rays. This work was done in 1916 by DeBroglie although the discovery of such absorption dates from Barkla's work in 1909.

In an X-ray beam there is present, in addition to the characteristic frequencies which arise from the vibrations of electrons within the atoms of the anticathode, more or less radiation of other frequencies below those which are characteristic. A haphazard jumble of disturbances of all degrees of suddenness accompanies the impacts of the various electrons of a cathode stream. These are analysed by the crystal spectrometer into a consecutive series of recurring disturbances which then have the appearance of

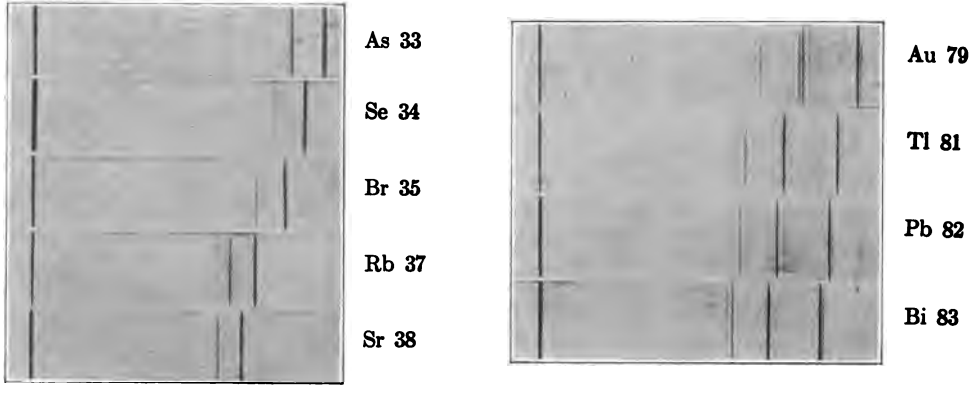


FIG. 25. Photographs of characteristic X-ray spectra. The greater the frequency of the rays the smaller is the separation between the central image and the characteristic spectral lines. The central images are in register at the extreme left. (Reproduced from memoir of Siegbahn.)

PLATE III

radiations of definite frequencies. A continuous spectrum is thus formed. The appearance, however, is due entirely to the regularity of structure of the crystal or other instrument of analysis and is not inherent in the X-rays themselves.

The amount of this general or so-called "white" radiation is relatively small and does not obscure the more pronounced characteristic radiation. At the top of Fig. 26, for example, there appears a photograph of the X-radiation from tungsten as taken through a crystal spectrometer, like that of Fig. 23, except that the slit $D$ is omitted so that a wide range of frequencies may reach the plate. In addition to the continuous spectrum of X-rays two series of characteristic lines are visible, namely, the K series near the central black band, and the L series further to the right.

The central black image corresponds to $X$ of Fig. 21. Each of the other lines corresponds to $X'$ of this figure for there is a different location of $X'$ for each frequency involved in the beam of X-rays. The separation of $X$ and each $X'$ is greater [1] the smaller the frequency of the vibratory motion which the crystal spectrometer is detecting. For tungsten with its high atomic number of 74 the K lines are due to radiations of correspondingly high frequency and are very close to the central image. The L series

[1] In the photographs of Fig. 25 the central image corresponding to $X$ appears at the extreme left. From these, it is seen that the higher the frequency, that is the higher the atomic number, the closer to the central image will be the spectral line corresponding to $X'$.

which have about one-seventh the frequencies of the K lines are well separated from the center.

The second photograph of Fig. 26 was made by inserting in the path of the X-rays from tungsten a thin sheet of molybdenum. The K lines are no longer visible. In fact, above a definite frequency all the radiation from the tungsten has been absorbed and for a certain region to the right of the central image, the photographic plate has been unaffected. If antimony, of atomic number 51, replaces molybdenum, of atomic number 42, the absorption band does not extend to as low frequencies. In general it has been found that the limiting frequencies at which absorption begins are sharply marked, are characteristic of the atom of the absorbing material, and increase with the atomic number.

Before carrying the discussion further an explanation must be given for two edges of light and dark which occur in the first photograph of Fig. 26. These are marked Ag K$\alpha$ and Br K$\alpha$. They are the boundaries of absorption for silver and bromine. They were obtained by inserting a thin film involving atoms of these substances. X-ray absorption is a function of the electrons within an atom and hence without prejudice an atom may be a partner in any sort of molecular union. In this particular case the film of silver bromide, AgBr, was the sensitized film of the photographic plate *itself*.

An element will absorb radiation of frequency higher than that of its own characteristic X-ray radiation. If, therefore, a given radiation is impressed successively upon the elements of the

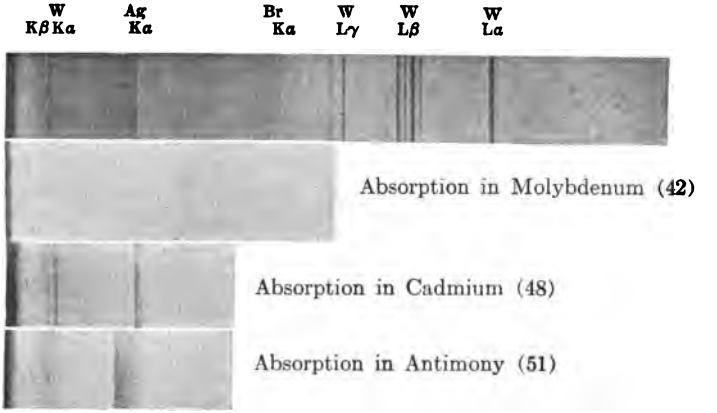


FIG. 26. X-ray absorption spectra. The upper photograph shows X-rays from a tungsten anti-cathode. The lower photographs show absorption of this radiation by plates of molybdenum, cadmium and antimony. (Reproduced from memoir of DeBroglie.)

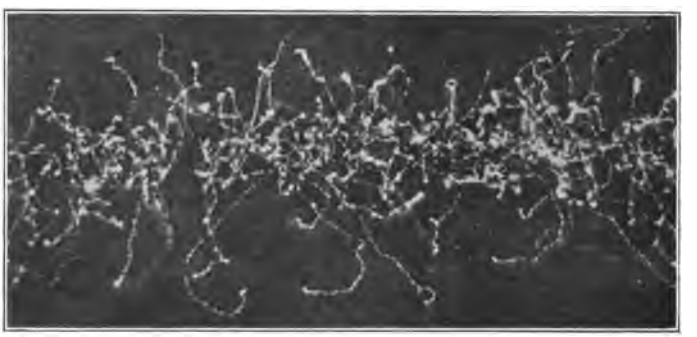

FIG. 28. The path of an X-ray through humid atmosphere. It is marked by the ionization trails of the electrons which it ejects from the gas molecules. (Reproduced from memoir of C. T. R. Wilson.)

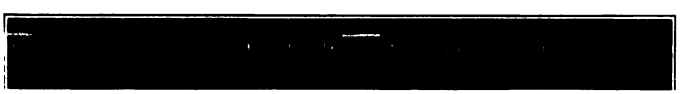

FIG. 31. A line spectrum of hydrogen. The hydrogen spectrum is bracketed by an iron spectrum which furnishes a comparison scale. (A section of photograph from memoir of H. B. Lemon.)

PLATE IV

periodic table there will be absorption by all elements of atomic numbers lower than that from which the radiation arises.

The phenomenon is further illustrated in Fig. 27. A series of elements were exposed to the K radiation of nickel (atomic number 28). For each element the height of the curve represents the absorption.

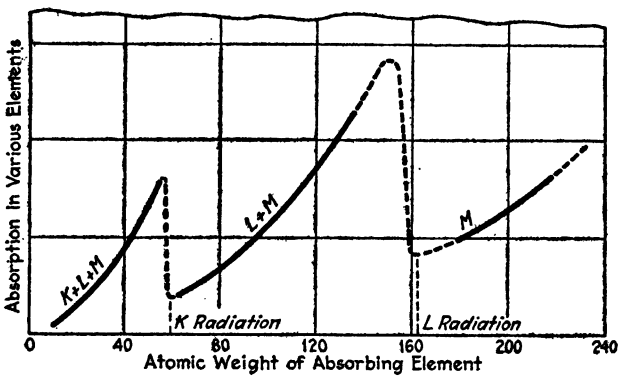


FIG. 27

Relation between absorption of X-rays and atomic weight of absorbing element. The K type radiation from Ni (atomic weight 58.7) was successively impressed upon various elements. For elements below Ni it excited K, L and M radiations. For elements of extremely high atomic numbers it excited only M radiations; for the intervening elements L and M radiations.

In each of the elements below nickel there is an absorption of the K radiation from nickel, for in each element the X-ray energy is absorbed by the electronic systems which then vibrate naturally to give off their own radiation, not only K type but also L and M types. The higher the atomic number the greater the amount of energy required to emit the characteristic radiation and hence the greater the absorption.

When nickel is reached, absorption abruptly ceases so far as it is due to energy which is converted into characteristic K radiation. There remains, however, a cause of absorption in the L and M types of radiation. These vibrations are of lower frequency and require less energy. As elements of still higher numbers are examined the absorption increases. The "rare earth" elements have not been examined, so that for this region the probable form of the curve is indicated by dots. For some element in this range the nickel radiation is unable to excite the L series but may excite a series of still lower frequencies known as M. Again the absorption increases as indicated in the figure.

Studies of absorption phenomena by DeBroglie and others are largely responsible for our knowledge of the atomic numbers of the elements of higher atomic weight. A great deal of evidence, however, besides that which has been presented in this chapter, confirms the modern physicist in his concept of atomic numbers.

# BETWEEN CHAPTERS

### A DIALOGUE

In one of Stevenson's fables the characters of "Treasure Island" come forth between chapters to discuss the author's plans for them. For writers of less ability the characters adopt tactics of heckling between chapters. In the present book there are only two characters if one does not include the formless and intangible spirit of energy. The burden of their complaint is the author's selection of their characteristics. For some time Proton and Electron have been objecting that they were incompletely described.

*Proton and Electron:* Why haven't you told how large we are?

*Author:* I have by implication. You are too small to see anyway.

*Electron:* We don't believe you know.

*Author:* What if I don't know exactly? You can't be greater in diameter than 0.000,000,0—

*Voice of Energy:* Stop! You are not paid by space rates. If you will degrade me and decrease my availability, wasting wood pulp by the page, refusing even to make the small conservation of my potentialities which simplified spelling offers, you might at least stop writing noughts. Can't you use powers of ten? Write it as $2\times10^{-13}$ or as $2/10^{13}$.

*Author:* Yes, I know; but it will make my pages

look mathematical and inhibit the General Reader.

*General Reader (by ether waves):* Don't mind me; I am about through with you anyway.

*Scientific Reader (through the same hypothetical medium):* I am through with you, too. You have approached the subject in an order which is impracticable for pedagogical purposes, starting with unknown electrons and then describing how they were discovered. Just take your last chapter. You beat all around the subject and didn't say that what Moseley found was a proportionality between the *square root* of the frequency and the atomic number.

*Voice of Energy:* Don't mind that fellow. I am the only important entity in the entire physical universe. He doesn't really know me. He speaks of me glibly at times but when he gets into a pinch he says its due to some kind of a force—that's his way of referring to me when I am getting a bit run down. Now, as to you. You tell me when you are going to give me a whole chapter to myself. You are ready to do it now. In fact, you got yourself in for it by flirting with my Quanta in the last chapter.

*Electron:* Oh! please, Father Energy, you know how my every motion conforms to your first and second laws. Don't insist. I feel sure he was going to discuss emission spectra of lower frequencies and then he would be discussing oscillations within the visible spectrum. And you know I just love to be seen of men. Or, perhaps he was intending to describe how swiftly I can fly when I receive from X-rays or ultra-violet light just one tiny quantum. And you know, Father Energy, he couldn't write

half a chapter on the photo-electric effect without saying something about these quanta in which you are so much interested.

*Proton:* That argument cuts both ways. Why shouldn't he treat us both alike? You know its our joint motion as atoms to which he referred once as thermal agitation. If he will write now about that subject he can't get far without introducing quanta. Father Energy himself knows that Planck's theory of quanta might never have received the attention it has if Einstein hadn't applied it to the problem of specific heats. If he starts with the motion and energy of molecules and atoms he is bound to give more ideas of their sizes and to explain how scientists know how many molecules there are in any volume of gas, and what Avogadro's constant is, anyway. And then he can't help emphasizing my point that even if you are larger than I am, still I am much more massive.

*Electron:* Yes, you are more massive, but what he said about you was that you had 1845 times as much inertia as I had. I don't believe he appreciates personalities like yours with too much inertia. Didn't he give you a new name? That shows he's radical and insulted you, too, hanging on you one of those newfangled names which some English scientists have only just suggested. If he thought so much of you why wasn't he respectful enough to call you a "positive electron" as all good scientists do?

*Voice of Energy:* Stop quarrelling. You are dissipating energy. All that you have said merely

shows the close interrelation of any one phenomenon of physical science to a large number of others. What does it matter to which portion of the subject he jumps next? Don't you realize that radioactive phenomena and now my quanta have shown that nature proceeds *per saltum?* Really, it isn't nearly as important where he jumps as how he lands.

*Proton:* Do you mean that I must go back and live with this electron in some dark atomic structure?

*Electron:* If it isn't dark my activities will provide the light.

(Exeunt Proton and Electron.)

*Author:* Well, they're gone. But what was that last remark of Energy as to how I am going to land?

# CHAPTER XI

## PHOTO-ELECTRIC EFFECTS AND THE QUANTUM OF ENERGY

Two phenomena are observable when X-rays impinge upon a substance. X-rays are re-radiated and electrons are ejected. The first phenomenon, which was discussed in the last chapter, has served to establish the quantitative relations between the nuclei of different types of atomic systems. It is characteristic of radiant energy of all frequencies. According to the frequency of the original vibration and according to the oscillating systems of the substance upon which it falls, radiant energy, whether light or heat, is absorbed and re-radiated with or without change of frequency. Of re-radiation with change of frequency an illustration in the visible range of frequencies is furnished by so-called fluorescent substances.

Just as substances exposed to X-rays give off their own characteristic vibrations when these are of lower frequency, so fluorescent substances when exposed to the invisible ultra-violet radiations will give off visible radiations. Electric arc-lights are quite rich in ultra-violet radiations, so that fluorescent substances exposed to such light will glow with their characteristic radiations. The effect is easily ob-

served also with sunlight, if a beam is allowed to fall on a glass vessel of kerosene. If the vessel is viewed at right angles to the beam the characteristic blue fluorescence of the kerosene may be observed.

The second phenomenon, that of the ejection of electrons, is also characteristic of all radiations within certain limits of frequency. Gamma rays, X-rays and ultra-violet light will all eject electrons from the substances upon which they fall. The limiting frequencies below which such ejection cannot occur lie in the range of ultra-violet and even visible light and depend, as we shall see, upon the atomic systems of the substance.

A picture of the phenomenon as it occurs in the case of X-rays may be quoted from a popular lecture[1] by Sir William Bragg. "Suppose that the target (anti-cathode) of an X-ray bulb were magnified in size until it was about as great as the moon's disk, that is, magnified a hundred million times. The atoms in it would be spheres a centimeter or so in diameter, but the electrons (and the nuclei, as well) would still be invisible to the naked eye. The actual distance from earth to moon would now correspond roughly to the corresponding magnification of the distance that ordinarily separates the bulb from the observer's apparatus (the substance under examination). We now shoot electrons (a cathode stream) at the moon with a certain velocity. Let us say that every second, each square foot or square inch, it doesn't matter which, receives an electron. A radia-

[1] The Twelfth Kelvin Lecture before the Institution of Electrical Engineers, 1921 (not literally quoted).

tion starts away from the moon, which immediately manifests itself by causing electrons to spring out of bodies upon which it falls. They leap out of the earth, here one and there one; from each square mile of sea or land, one a second or thereabouts. They may have various speeds but none exceed, although some will just reach, the velocity of the original electrons that were fired at the moon. That reduced again to normal size is the process that goes on in and about an X-ray bulb. It is part of a universal process going on wherever electron or wave falls on matter and is one of the most important and fundamental operations in the material world."

The electrons which are ejected when an X-ray passes through a substance start off with speeds and energies like those of the cathode rays which originated the radiation. As they pass through the substance they disturb other electrons and hence ionize large numbers of the atoms. Except for such dodging as may be required to avoid adjacent systems the ejected electrons move at right angles to the direction of the beam. Their paths have been photographed by C. T. R. Wilson, using his discovery of cloud formation in humid atmosphere. In Fig. 28 is shown the path of an X-ray through a gas. It is marked by the activities of the electrons which it ejects. Their trails of ionized atoms, as shown by the drops, start at right angles to the path of the ray, which is lengthwise through the center of the picture.

The phenomenon of the ejection of electrons, when the exciting radiation is ultra-violet or lies within the

visible range, is known as the photo-electric effect. It promises to be of wide scientific interest, for it is apparently the cause of photo-chemical effects like those utilized in photography, of photo-synthesis in the formation of carbohydrates in plant life, and even of the effect of light on the retina of the eye.

When light of a certain minimum frequency is incident upon a substance electrons may be ejected. The phenomenon was first noticed by Hallwachs in 1888, who found that a metal plate became positively charged, or lost its negative charge, if it were originally negative. This is what should happen if electrons are emitted by the plate.

Present-day theories as to this effect are the result of observations by a large number of experimenters, to which a valuable addition was made by Einstein in terms of the quantum theory. This theory, which received some mention on page 119, was propounded by Planck about 1901 to explain certain phenomena of radiation with which we shall deal later. In 1905 Einstein applied it to photo-electric effects and predicted that the emission of electrons would conform to a simple relation.

He assumed that the electron, which is emitted, leaves the metal as the result of its absorption from the incident radiation of one quantum of energy. A quantum, as has been said, is a small amount of energy, numerically equal to the product of Planck's constant, $h$, and the frequency, $n$, of the radiation, and hence symbolized as $hn$. The energy with which the electron leaves the surface is less than the absorbed energy, $hn$, by the amount expended in get-

ting free from the atom, much as the energy of a bullet at the muzzle of a gun is less than that contributed to it by the explosion because of the frictional losses in the barrel. For any substance there will be, then, a frequency of radiation, $n_0$, such that the quantum contributed to the electron just represents the energy required to set it free of its former associates. For a quantum at this frequency it becomes free but is too exhausted to move beyond the threshold. For any exciting frequency, as $n$, which is higher than this threshold frequency, $n_0$, the electron will have a net balance of kinetic energy which it may expend beyond the confines of its atomic home. This balance is always equal to the difference of two quanta, one of value $hn$ and the other $hn_0$.

This is Einstein's relation. At the time he made his prediction there was no experimental evidence that the kinetic energy with which electrons are emitted should increase proportionately with the frequency, $n$, of the light. The relation has been verified since and this successful application of the quantum theory is strong evidence for the correctness of the hypothesis of quanta.

One of the most exhaustive investigations of Einstein's expression was carried out by Millikan. Not only did he verify the relationship but he obtained from his experimental data a very exact value for Planck's constant, $h$. He measured frequencies and energies and hence $h$, the other magnitude involved in the relationship, was determined. The fact that it was constant, independent of the frequency of

the exciting light, was the proof of the correctness of the relation under examination. The method followed was essentially that of previous investigators of the photo-electric effect. The accuracy of Millikan's determination of $h$ lies partly in the precision of his observations and partly in his use, for the calculation of $h$, of the modern value for the charge represented by an electron, which he had determined by the oil-drop method.

The quantity of electricity represented by an electron enters into the relationship because of the experimental method which was followed in determining the energy of the emitted electron. Suppose the plate or electrode which is to be exposed to the radiation is made positive with respect to its surroundings by connecting between them a battery. The plate then starts with a deficiency of electrons and its surroundings have an excess. If an electron is moved from the positive plate to a nearby object it will acquire a certain amount of potential energy. In order that it shall of itself perform such a motion it must leave the plate with a kinetic energy at least equal to this potential energy which it will have at the completion of its journey. By adjusting the potential applied by the battery to a value just beyond the possibilities of the emitted electron the latter may be just prevented from reaching any of its negative surroundings. The value of the potential energy of an electron on the negative body then measures the kinetic energy of the emitted electron.

Into the evaluation of this potential energy there

enters the charge on an electron. You will remember that for simplicity we took the electron as the unit of electricity and the potential energy of an electron as the unit of electrical potential. The present accepted units of charge and potential were adopted, however, before the electron was discovered. The unit of electrical potential is the potential energy of unit charge, but unit charge is not the electron. Hence, to express the potential energy of an electron in the accepted units one must know the relation between unit charge and the electronic charge. This relationship Millikan had determined very accurately by the method described on page 94.

The photo-electric experiment was performed in a highly evacuated vessel for collisions with gas molecules would mask the effect. The substances used were the alkali metals, lithium, sodium, and potassium, which are very markedly electropositive. Their atoms each have one more electron than is desirable for a stable configuration and probably for this reason they are most sensitive. They will respond to the frequencies of the visible spectrum as well as to the ultra-violet frequencies.

Cylindrical plates of these materials were mounted as shown in Fig. 29, so that one at a time could be studied. By magnetic control from outside the vessel a plate could be turned to the knife $S$, which removed a thin paring and left a fresh surface. The plate with its clean surface was then turned into contact with electrode $C$, so as to determine what portion of its potential was due to the so-called "contact electromotive force," that is to differences in

potential which are always present between dissimilar substances. It was then turned to face the wire gauze cylinder *G*, which effectively constituted its surroundings. Whether or not any electrons reached this cylinder was determined by observing an electrometer connected to it at *B*.

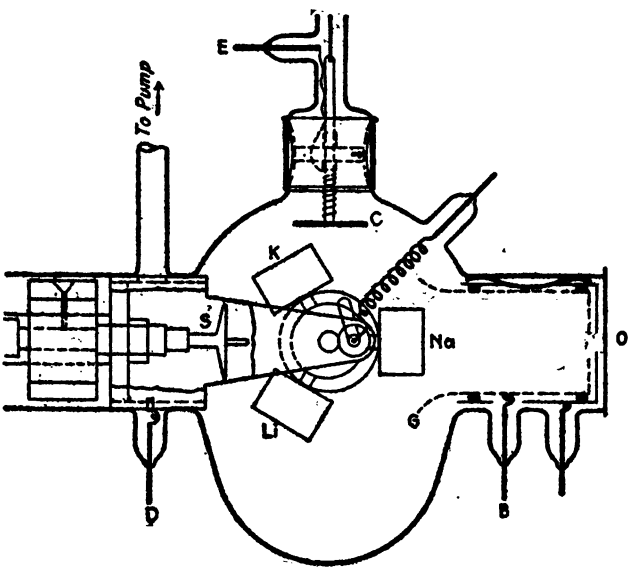


FIG. 29

Cross-section of Millikan's apparatus for measuring photo-electric emission. Light entering at *O* ejects electrons from the disc *Na*. If these reach the wire gauze cylinder, *G*, a deflection is produced in an electroscope connected to the terminal *B*.

The value of *h* which was obtained will be given in the Appendix with other important physical magnitudes, since statements of magnitude involve choices of units and in the case of scientific units considerable explanation is usually required.

Millikan also verified a phenomenon, first observed by Lenard in 1902, which was implicitly covered by our earlier discussion of Einstein's application of the quantum theory to photo-electric emission. The energy with which the electron is ejected depends only upon the substance and the frequency. It is independent of the intensity of the light which causes the ejection. If the light is intense more electrons are emitted but none leaves with greater energy. This same phenomenon also occurs in the case of X-rays and of gamma rays. The amount of light determines the number of electrons which are ejected but does not affect their individual energies.

For X-rays the converse phenomenon has been investigated. Duane and Hunt and also Hull have studied X-ray radiation and found that the highest frequency in the general or "white" radiation corresponds to that which should arise according to the quantum theory. The product of this highest frequency by Planck's constant is always equal to the energy of the individual electrons in the cathode stream which causes the radiation.

From all these experiments it seems certain that whenever electronic impacts give rise to radiation the energy associated therewith is always proportional to the frequency and the factor of proportionality is Planck's constant, $h$. Similarly, it appears from all measurements where electrons are emitted by radiant energy that the energy associated with the individual electrons is always related to the frequency of the radiation by this same constant. The result is that the scientific world has quite unani-

mously accepted it to be a fact that energy is emitted in quanta.

When an electronic system expends energy it does so in definite amounts. Is energy granular or atomic in character? Must we think of it as transmitted through space like a corpuscle? And then, is each corpuscle of energy received *in toto* by a single electron? Since an electron can emit only definite quanta of energy, can it receive energy in amounts less than a quantum? If it receives and emits only by quanta, presumably its own total energy at any time is some integral number of quanta. What in any case is the mechanism which is involved?

Such are the questions which confront the scientist of today. Evidence as to the correct answers is lacking but it may well be forthcoming in the near future. Such evidence as now exists only makes the problem more complicated. Consider, for example, the question as to the absorption of energy.

The moment a substance is exposed to light of the proper frequency the photo-electric emission begins. This would appear to indicate that there was a hopperful of energy in some electronic system which was tripped off, as by a trigger, and allowed to discharge. The energy which is released was either obtained from the beam of light, despite the short time of exposure, or was already stored in the atomic system. The further fact that the energy of the emitted electron is the same whether the intensity of the light is large or small would seem to indicate such a storage. Photo-electric phenomena occur in such feeble light as would correspond to an ordinary

candle at a distance of three miles. (The number of electrons which are emitted each second is greater for greater light intensity even though the energy of each is a function only of the frequency.) Throughout the entire range of intensities, which would correspond to bringing the candle from miles away to within an inch of the plate, the energy of an emitted electron is always one quantum.

For the moment, then, the evidence adduced seems to favor a theory of continuous absorption of energy, its storage, and release in quanta when the electronic oscillator is disturbed. But if there is such a trigger action why should the action, and the amount of energy which is released, depend upon the exciting frequency? One might think of a tuned system which responded only to a single note, but why should the amount of the response depend upon the note? It should make no difference what frequency of radiation disturbs the hopper and allows it to dump its load of energy. Why, also, should the output depend solely upon the frequency and not upon the type of hopper, that is upon the type of atom? It does, although the amount of energy which is expended by the emitted electron in passing through surrounding systems does depend upon the atomic nature of the substances. The analogy of the hopper which is released by a trigger action seems to be contrary to the observed facts. We are forced, therefore, to the conclusion that the energy of the escaping electrons is derived from the incident light.

But this conclusion brings us back to the difficulty as to the intensity of the light which excites the

effect. According to the theory of radiation which is commonly accepted, the energy leaving a source is uniformly distributed over a spherical surface which increases constantly in size as the radiation proceeds outward. The effect may be seen in the widening circle of a wave caused by dropping a stone into water. An object upon which such a wave front impinges subtracts from it only the energy corresponding to the proportion of the total wave front which strikes the object. The effect is well known to sailors of small boats who have received the wash of a steamer before its wave front was much enlarged. If we calculate on this basis the amount of radiant energy which in one second should reach a tiny atom we find cases where the amount is so small that billions of seconds would be required before the atom could acquire the quantum of energy which it radiates so promptly.

This difficulty would be solved if energy were not resident in the medium, as it is in the obvious mechanical case of the water wave, but had a corpuscular structure. On this basis, when a body radiated energy it would really be shooting out in all directions a shower of invisible particles, small bundles of energy. The electron must then receive or reject a whole bundle. The picture of the ejection of electrons by X-rays which was quoted on page 140 would be explained if the X-rays were really small bullets of energy which followed radial paths outward from the anti-cathode. What appears to us as a continuous distribution of energy in a wave is probably not really continuous but conforms in analogy to a fine

shower of rain such as one experiences when a fog blows in.

Matter which originally appeared to mankind as continuous and infinitely divisible has been shown to be atomic. Electricity, whose phenomena appeared those of an invisible fluid, has proved to be granular in structure. Why should we not expect that energy also should prove to be not infinitely divisible but transmissible only in finite amounts? There are three objections: First is the incompleteness of the evidence, second the subconscious effects of our scientific traditions and training, and third, a definite piece of evidence against the hypothesis which as yet has not been explained away.

A corpuscular theory for light was commonly accepted in Newton's time, despite a growing mass of evidence and theory in favor of a wave motion through an ethereal medium. Reflection was then explained as due to an attraction of the reflecting surface which bent toward itself the swiftly moving corpuscle, which the human eye later apperceived as light. As it happens, our present concept of reflection as re-radiation would also accord with a corpuscular theory for the transmission of energy through space.

The evidence which finally dispossessed the corpuscular theory arose in connection with the phenomenon of interference.[1] In its simplest form interference phenomena take place as illustrated in

[1] We have already implicitly applied the theory of this phenomenon to the case of the crystal grating for the spectral analysis of X-rays.

Fig. 30. Imagine a source of radiant energy to transmit to two slits, shown in cross section at *a* and *b*. From these two slits the energy spreads through the ether just as if the slits were separate homogeneous sources. For simplicity we imagine the light to be a single frequency. From these slits there then spread out a succession of wave surfaces. In cross section these have much the appearance of surface waves

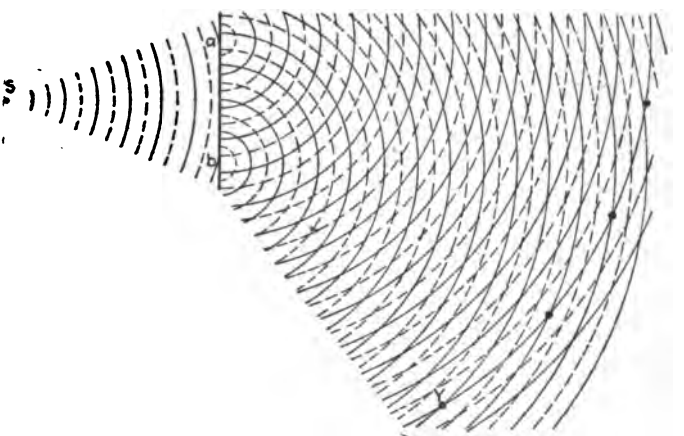


FIG. 30

Diagram illustrating interference of wave trains.

which are produced in liquids by regularly recurring disturbances. Where the trough of one meets the crest of another, interference occurs. Where trough coincides with trough, or crest with crest, there is reenforcement and a greater displacement. The figure represents an instantaneous view of the transmission and shows crests as full lines and troughs as dotted lines.

It is easy to pick out a succession of points where

either type of interference phenomenon is occurring. At some point like *Y*, for example, the disturbance from *a* is three whole wave lengths ahead of that from *b*, and reenforcement occurs.

In the present case there is a definite limit to the number of wave lengths by which the two disturbances can differ. With the interferometer, however, which was devised by Michelson, large differences in path may be obtained. Differences of as much as several thousand wave lengths have been instituted between the paths of the beams from two homogeneous sources and still the phenomenon of interference has been observable.

The objection of the necessity of conforming to the known facts of interference is not, however, unsurmountable.[1] It would seem to demand that the bundle of energy should have a length which might be large in terms of wave length but would be small as compared to the distance the energy travels in each second. In some way this bundle might also contain within itself something of the structure of a

[1] It may well be that the two aspects of radiant energy which we recognize as "quantum" and as "wave motion" are not mutually incompatible. Such a possibility is noted by way of illustration in that most interesting book on relativity, Professor Eddington's "Space, Time and Gravitation." He says, "Physical reality is the synthesis of all possible physical aspects of nature. An illustration can be taken from the phenomena of radiant energy or light. In a very large number of phenomena, the light coming from an atom appears to be a series of spreading waves. In many other phenomena the light appears to remain a minute bundle of energy, all of which can enter and explode a single atom. There may be some illusion in these experimental deductions; but if not, it must be admitted that the physical reality corresponding to light must be some synthesis comprehending both these appearances. How to make this synthesis has heretofore baffled conception. But the lesson is that, . . . reality is only obtained when all conceivable points of view have been combined."

train of waves which would produce interference effects with bundles which had been dispatched by other routes.

In the absence of direct evidence some incline toward one side and some toward the other of this question. Perhaps the lay reader will have less to unlearn in the future if he accustoms himself to think of there being shot about in the physical universe bundles of energy, the arrival and departure of which are manifested by changes in atomic systems.

# CHAPTER XII

## LIGHT RADIATION AND ATOM-MODELS

THE concept of an atom with a nucleus was due to Rutherford whose experiments on the scattering of alpha rays were explainable, as we have seen on page 102, by the assumption of such an atomic structure. In terms of this structure it then became necessary to explain other known phenomena, particularly that of the radiation of light from atoms. The attempt was made by Bohr in the years immediately following 1913.

He started by pointing out that the planetary electrons of the Rutherford atom-model would be unstable, according to the recognized laws of mechanics, if their rotation was assumed to be the cause of light radiation. Rotating electrons, as was mentioned on page 78, influence other electrons. In so doing they impart some of their energy. Consider for a moment what the effect would be if the rotation of the planetary electrons was accompanied by a radiation of energy.

Electron and nucleus tractate, but the kinetic energy of the electron prevents its falling into the nucleus, just as planets maintain stable paths about the sun by virtue of their kinetic energy. If, however, this energy is gradually subtracted by radia-

tion, the electron will fall in towards the nucleus. Due to its changed orbit it will have a changed frequency of rotation. A continuous change in frequency, therefore, should be noted in the light from a tube of gas like hydrogen through which an electric current is being passed by the motion of the ionized gas molecules. No such change is noted, for the spectral lines of the chemical elements are definite, unvarying, and characteristic.

So-called classical electro-magnetic theory is incapable of accounting for radiation in terms of planetary electrons rotating about a nucleus. Bohr, therefore, applied to the phenomenon the quantum hypothesis which had already served good purposes in other fields of inquiry. His radical assumption is the possibility of non-radiating orbits. In the Rutherford-Bohr atom-model a planetary electron rotates without the emission or absorption of energy. It has a steady orbital motion which represents a condition of equilibrium so far as concerns changes in energy.

An electron may, however, be caused to change its orbit and the emission or absorption of energy is assumed to accompany this change from one equilibrium state to another. During the change of an electron from a larger to a smaller orbit radiation of a definite frequency is emitted and the amount of energy involved is always one quantum. By such a theory it was presumed that the spectral lines of the various elements could be accounted for. Characteristic spectra are emitted by the various elements, as we have seen in Chapter XI, when the

electronic structures are disturbed by the impacts of a cathode stream. Vibration frequencies of smaller values, corresponding to the ultra-violet and visible range, arise from less violent disturbances, such as occur for example in the ionized gas or vapor of a highly evacuated tube which is conducting electricity.

When an electric current is passed through a gas light is emitted.[1] By using a spectrometer or a grating, involving the principles of interference which have been mentioned in previous chapters, this light may be analysed into a series of spectral lines, similar to but more numerous than those appearing in an X-ray spectrum. It is found that any element produces a spectrum in which lines recur at intervals throughout a given frequency range. These lines form a series, the frequency of each member of which may be calculated from that of the highest frequency by very simple arithmetic. In the case of incandescent hydrogen three such series are known: one in the visible range of frequency called the Balmer series; one in the region of lower frequency, the infra-red region, which is known as the Paschen series; and the third, known as the Lyman series, in the ultra-violet.

When one knows the highest frequency of a series of spectral lines the calculation of the other frequencies is a piece of arithmetic which impresses one with the probability that the order of nature is in-

[1] Energy is absorbed from the source of electric current in the act of ionization and radiated when recombination occurs.

herent in the granular structure of electricity and energy.

Start with the simple series of numbers, 1, 2, 3, 4, 5 and so on. Write the reciprocals of these, thus, 1, 1/2, 1/3, 1/4. Then write the squares of these reciprocals, thus, 1, 1/4, 1/9, 1/16. Now assume that we know for any atomic system its highest possible frequency of radiation. As a matter of fact, it is a little over three million, million, million, and is known as the Rydberg constant. To find the lowest frequency we take the difference between 1 and 1/4 and multiply it into this constant frequency. We thus obtain the line of longest wave length. For the next line of this same series we multiply the Rydberg constant by the difference between 1 and 1/9, and so on for the other lines of the Lyman series.

The Balmer series, which has its head (highest frequency) in the visible spectrum, is found by taking the second number of the series of squared reciprocals, namely 1/4 and subtracting from it the next, namely 1/9, and then proceeding as before. For the third series, which has a head of still smaller frequency, we start with the third term, and subtract from it successively the fourth, fifth, and succeeding terms.

These series involve a relatively large number of terms. For example, in the spectra of certain celestial bodies thirty-three hydrogen lines have been observed which correspond to those calculated for the Balmer series. Fig. 31 (Plate IV, opposite p. 131) shows a photograph of a hydrogen spectrum. In the

laboratory, however, only twelve lines of the series are reproducible by discharging electricity through a tube containing a little hydrogen gas.

According to the Bohr theory the higher the number in the series the greater will be the radius of the electronic orbit. The greater this orbit the greater is the apparent size of the atom, as was pointed out on page 13. If, therefore, atoms are to have large electronic orbits their centers must be widely separated, and hence the gas density must be small.

At ordinary atmospheric pressure, however, the molecules in a gas are relatively close together. As the number in any enclosure is reduced the pressure which they exert, or, what is equivalent, the external pressure necessary to constrain them to this volume, is correspondingly reduced and the average distance between molecules is increased. With the modern vacuum pump the number of molecules in a given vessel may be so reduced that on the average individual molecules will travel twenty miles between collisions with other molecules within the tube. (Of course we are not considering reflecting collisions with the molecules of the walls.) Under these conditions, despite the fact that the tube will still contain about a thousand million molecules in each cubic centimeter, the average distance between molecules is enormously greater.

Only in a highly evacuated tube would there be the possibility of large electronic orbits. The corresponding spectral lines are not visible, however, because the whole mass of the gas in the tube is insufficient to give sufficient intensity of ra-

diation to permit detection. In the neighborhood of stars, on the other hand, the mass of the gas is sufficient and its rarefied condition meets the requirement as to gas density so that lines corresponding to larger orbits may be observed. On the basis of the Bohr theory, therefore, the failure of experimenters in the laboratory to reproduce or to observe the higher frequencies of the Balmer series becomes explainable.

Apparently, also, there is no normal size for any atom. Its effective diameter depends upon the largest orbit of its electrons. Whether or not an electron moves into a larger orbit depends upon the restraining effect of neighboring systems and upon the violence of the disturbance to which it is subjected.

The smaller orbits are more stable because of the greater tractation between nucleus and electron. Hence an electron which has been displaced to a larger orbit returns to one of smaller size and greater stability. In so doing it radiates a quantum of energy and the value of the frequency which determines that quantum is apparently that of the orbit which it assumes. For large displacements the electron may assume successively smaller and smaller orbits and thus give rise to a succession of lines in a spectral series.

When a large number of atoms are involved, as there must be if a measurable effect is to be observed, individual atoms may be emitting different characteristic frequencies. To the observer, however, there appears a number of lines of the series, just as if they were simultaneously produced by a single atom. The

fact that they are intermittent and originate in separate atoms is obscured, since he deals with them statistically in terms of average effects.

Bohr's method and its successes may now be briefly summarized. He dealt most successfully with the hydrogen atom which has only a single electron and, therefore, the simplest possible structure. Upon the assumption of non-radiating orbits he was able to apply to the motions of electrons in such orbits the same mechanical principles as hold in the case of planetary rotations in celestial systems. By the adoption of the quantum hypothesis he was enabled to calculate the energy changes involved in a change from one non-radiating orbit to another. In calculations he had at his disposal previously obtained values for the mass of an electron, for its charge, and for Planck's constant. In terms of these he calculated the diameter of a hydrogen atom and the corresponding frequency of an electron revolving in this orbit. He also calculated the amount of energy required to displace an electron completely from the hydrogen atom and thus found the potential necessary for the ionization of hydrogen. His values agreed very well with those obtained by other means.

He further calculated, on the basis of his theory, the Rydberg constant for hydrogen. The value thus derived differed only one per cent from that obtained by a study of spectra. At that time the head of the Lyman series had not been discovered, and its existence was in effect predicted by the Bohr analysis.

Similar successes[1] also accompanied the theoretical study of the frequencies which were to be expected in the case of helium.

In the Bohr formulæ there are implicitly contained a large number of statements which have since been checked. His expressions for hydrogen and helium show the entire range of possible frequencies. The theory, however, has been extended by Sommerfeld who endeavored on the basis of an ellipticity in some of the orbits to account for the fact that the characteristic lines are not always single[2] as would be required by the simple theory of circular orbits.

It has already been stated that three series of characteristic lines appear in the X-ray spectra of the elements above sodium and that the X-ray spectra of the elements below sodium have not yet been determined. On the basis of the Bohr theory, which implicitly includes the relation determined experimentally by Moseley, it is now possible to assert that the Lyman, Balmer, and Paschen series for hydrogen are the K, L and M series of its X-ray spectrum. As the atomic number decreases, the frequency of the characteristic X-ray spectrum also decreases. If this relation is extended by extrapolation to hydrogen it gives for each of the three X-ray series the

[1] On the other hand, there are several observable phenomena which have not been amenable to treatment on the Bohr assumptions. The Bohr atom is, at present, largely a convenient assumption.

[2] It has also been suggested by A. C. Crehore that the multiplicity of fine lines which appear in spectra is due to the nature of the paths which displaced electrons follow in their return toward the nucleus.

head line (highest frequency) in one of the three hydrogen series.

It appears, therefore, that the mechanism for the production of light is fundamentally the same as that for X-rays and that the only difference is one of frequency. The X-ray spectra are merely the highest frequencies for atoms of large atomic number. Below each of these highest frequencies there is a series of terms representing frequencies some of which may not be visible under experimental conditions.

In the case of the metals the spectra which are excited, when an electric arc is formed in the metallic vapor, are complicated by hundreds of lines. Analysis has not yet been accomplished for these cases but it seems safe to consider that the lines in these arc-spectra represent lower frequencies in series which are headed by the characteristic X-rays.

Bohr's formulæ implied between the different series of X-ray spectra a simple relationship which goes far to indicate the fundamental correctness of his assumptions. The relationship was verified by reference to the experimentally determined facts. In the K series which is shown in Fig. 26, the line of longest wave length (smallest frequency) is designated by alpha, and the next by beta, after the conventional manner for all spectral series. According to Bohr's theory the difference in frequency between the beta and the alpha lines in the K series of any element should be the frequency of the alpha line of the L series.

This is understandable if we think of the alpha line in the K series as due to jumping from orbit 2 of Fig.

32, to orbit 1; of the higher frequency beta line, with its larger quantum, as due to jumping from orbit 3 to orbit 1; and of the alpha line of the L series as due to jumping from orbit 3 to orbit 2. The same idea may be obtained also by reference to the arithmetical operations of page 158.

The permanent configuration which is reached when an electron changes in orbit is always one in the formation of which the maximum amount of

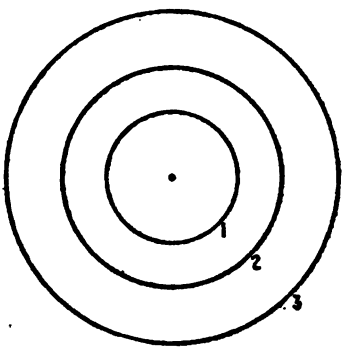


FIG. 32

Simplified diagram of electronic orbits in the Bohr atom-model.

energy is emitted. The extreme case occurs when an isolated electron joins a nucleus in the formation of an atom or neutralizes the positive charge possessed by an atom which by ionization has already lost an electron. For this reason radiation of line spectra occurs only in the case of an ionized gas. It does not accompany the process of ionization which absorbs energy but only the process of recombination when this energy is released.

For the basic ideas involved in the Bohr atom-model there is a large amount of evidence. It will

be noticed, however, that it does not conform to the picture of atom structure which was given in our early chapters, where the electrons were assumed to occupy relatively fixed positions in the atom. The concept of definitely localized electrons is highly satisfactory to the chemists who have found it to explain not only valence in chemical combinations but also many phenomena like the miscibility of different liquids, tendencies to vaporize, and hence melting and boiling temperatures. In such matters molecules which are believed to have like shells of electrons are found to have similar properties.

Between the chemists who are interested in molecular combinations and such physicists as are concerned with radiation there is at present established a gulf. Each finds his own atom-model most convenient and satisfactory. The chemical model is due to a number of scientists, chief of whom are Lewis, who first suggested its general features, and Langmuir, who has elaborated and extended it. It requires that the electrons effective in valence relations shall be relatively fixed. The Bohr atom requires that some, at least, of the electrons shall be in rotation.

It seems quite probable, nevertheless, and indeed more or less inevitable, that the two conditions are not hopelessly conflicting and mutually impossible. According to the chemists' construction the valence electrons in all except a few of the atoms are in external shells within which are other shells of electrons. Perhaps these inner shells contain the rotating electrons which determine the radiation of the

ionized atom. In the case of the elements between lithium and argon, however, all except two electrons are in a single shell. It is possible, therefore, that future investigations[1] of these elements will lead to evidence upon the basis of which a reconciliation may be possible, and the salient features of both models may be retained.

That the electrons of an atom are in rotation at least while light is being radiated is well proved by other phenomena which antedate our knowledge of electrons. Zeeman in 1896 discovered that a spectral line which originated from a gaseous source, placed in an intense magnetic field, appeared as three lines when the magnetic field was at right angles to the direction of the propagation of the light. The central line had the original position. The other two lines appeared on opposite sides of the original, one representing a slight increase in frequency and the other a corresponding decrease.

For simplicity of discussion let us imagine the source to consist of only three atoms, in two of which the electronic orbits are coaxial with the electronic streams whose motions establish the magnetic field. Suppose the directions of rotation in these two orbits are opposite. Now apply to these rotating electrons the laws stated on page 83 and it will be seen

[1] Characteristic X-rays are produced by the return of an electron which a cathode particle has knocked out of its normal position in an atom. Upon assumptions as to the distribution and orbital conditions of the electrons in an atomic system, it is possible to calculate for any element the "critical absorption" frequency for any given type of radiation, e.g., the K-type. Calculations were made by Duane (1920) upon the assumption that the distribution of electrons was that of the Lewis-Langmuir "static" atom. These agree very well with the experimentally observed frequencies.

that one is urged in toward the center of its orbit and the other is urged out. The result is that one acquires a slightly larger orbit and smaller frequency while the other acquires a smaller orbit and higher frequency. The orbit in the third atom we assume to be in a plane at right angles to the orbits of the other two atoms and it is unaffected by the magnetic field. The result is the three lines described above.

# CHAPTER XIII

## MORE EVIDENCE FOR THE QUANTUM HYPOTHESIS

In preceding chapters there have been mentioned two types of emission spectra, line and continuous. Of these the line spectrum is the more interesting. It is emitted by elementary substances which are in the state of a gas or a vapor, when the electrons have been displaced to new orbits or completely detached from the atoms. The return of an electron is accompanied by a radiation of which the frequency is characteristic of the element and the energy equal to one quantum. Line spectra are due to the natural vibrations of electrons and atomic nuclei.

A continuous spectrum, on the other hand, is a phenomenon of substances in the solid or molten-liquid state where the atoms are packed relatively close together. The atomic systems no longer function as untrammelled individuals but as members of a large and unorganized crowd. Each is limited in the expression of its tendencies (line spectrum) by the interrelations and reactions with the other systems of its milieu. Energy, imparted to the atomic systems under these conditions, results in chaotic motions on the part of all, which then proceed to jostle and crowd each other. Instead of a clear individual expression, which is characteristic of the

atomic type, there arises a roar of notes, expressive only of conflict and chaos. No longer are types easily distinguishable by characteristic lines for the spectra are continuous. Of this phenomenon all incandescent solids are examples.

When the disturbance is excited by impacts, as in the case of "white" X-rays, the highest frequency which is radiated is determined by the quantum of energy which is brought to the radiating substance by an impinging electron. A quantum relationship is also involved in radiations of lower frequency.

Under the conditions where a continuous spectrum is produced the normal oscillating systems of nuclei and planetary electrons are altered by the close presence of other systems. An electron is no longer concerned only, or even primarily, with its natural oscillation, for the electrons of each atom are forced to adapt their motions to the external influences. To all effects and purposes, therefore, the radiating body contains at any instant a very large number of oscillating systems which differ markedly from one another in form of vibration and in frequency. Molecules and atoms, as well as the intra-atomic elements, enter into oscillation. It is a mad dance, in which the partners are changing from instant to instant, each pair dancing to its own tune. Where molecules and atoms are vibrating, frequencies of infra-red radiation are produced. Where an electron is a partner the frequency is that of ultra-violet light. In the visible range fast vibrations of atoms or slow vibrations of electrons are presumably the cause of the radiation.

When we speak of atoms as responsible for radiation we do not mean neutral atoms, but, instead, those which are electrically charged as by the temporary loss or gain of an electron. That such atomic systems exist in solids we have seen in considering conduction of electricity through metals. High temperature, with its increased molecular agitation, also favors the formation of such atomic oscillators.

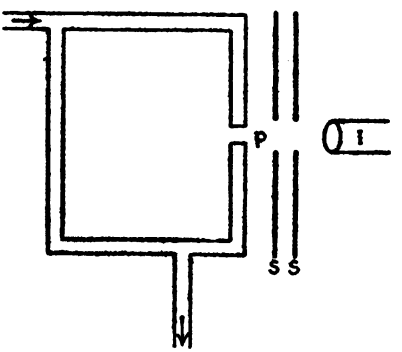


FIG. 33

Cross-section of a uniform temperature enclosure, showing at *p* a peep-hole for studying the radiation within. A circulation of steam maintains the temperature. Screens *SS* shield the measuring instrument *I*.

Due to close packing of molecules, atoms, and electrons, any solid body possesses a large number of oscillators of different electrical and geometrical dimensions and hence of various frequencies. Such a body, therefore, emits or absorbs a continuous band of frequencies. The emission is a commonly observable phenomenon. As a metal body, for example, is caused to rise in temperature it radiates heat and finally, becoming dull red, starts to radiate visibly. As the temperature is still further increased

it radiates still higher frequencies, becoming incandescent when its spectrum includes the visible range. The absorption phenomenon is not so easily observed. Let us suppose, however, that a radiating body is placed in an enclosure, as that of Fig. 33. Let the body be in equilibrium with the walls of its enclosure, that is with its surroundings, receiving from them by radiation just as much energy as it in turn is radiating to them. If either partner in this exchange were to absorb more radiation than it emitted its temperature would rise. The assumed condition, therefore, is one of temperature equilibrium and the body is said to be in a uniform temperature enclosure.

The assumption of an equality of exchange means that the radiation at any point is not affected by the nature of the body or its surroundings, nor by their relative location. For example, if part of the surface is covered with lampblack it absorbs nearly all of the radiation which falls upon it, but it must radiate an equal amount to satisfy the condition of equilibrium. Similarly, if part of the surface is covered by polished metal it will reflect most of the radiation and hence need radiate less to equal what it absorbs. The radiation within a uniform temperature enclosure is thus everywhere the same.

For this reason it is impossible by the radiation to distinguish one part from another. Within a cave all objects are equally black unless there is light from an entrance, or unless the condition of equilibrium is violated by the presence of a torch, which is an object of higher temperature, not in equilibrium with

its surroundings. Similarly if one looks into a crucible or into a large furnace when conditions are stable. There is a glare of light, but the inner surfaces are just as indistinguishable as are those of the cave where the temperature is lower.

Within a uniform temperature enclosure the radiation is altered in intensity and in quality only as the temperature is altered. For this reason such radiation is usually called "temperature radiation." The enclosure itself is a more or less artificial condition, an ideal or limiting case of equilibrium, which has been adopted by scientists because it permits them to concentrate their attention on the medium within the enclosure. In general, bodies are not in temperature equilibrium with their surroundings, and particularly not when these include a human observer. By his temperature sense he is frequently able to detect a lack of temperature equilibrium between himself and his surroundings.

Two important laws as to temperature radiation have been known for many years. To appreciate them we must decide upon a method of measuring temperature. In scientific work temperature is measured in degrees centigrade, each nine-fifths of a degree Fahrenheit, but the zero is the so-called "absolute zero."

This is based upon a phenomenon of gases. When a gas is heated one degree it is found that the haphazard molecular motion of its molecules is increased and that the pressure which it exerts upon the walls of its container is also increased by about one-273rd part of the pressure which this same volume of gas

would exert at zero degrees centigrade (32° F.). Conversely, if it is cooled by an equal amount there is a similar reduction. The explanation of the pressure is found in the impacts of the molecules on the sides of the container, battering it like a steady rain. The effect of temperature changes is explained on the basis of additions of kinetic energy to the molecules of the gas or of subtractions and hence of corresponding alterations in their average speeds.

Actual gases condense into liquids and freeze into solid form at low temperatures (and under high pressures externally applied). The scientist, therefore, establishes an ideal thermometer by using an ideal and imaginary gas which will retain throughout all possible ranges of temperature the characteristic which actual gases like hydrogen show at ordinary atmospheric temperatures. Except for the low temperatures his ideal thermometer is identical in behaviour with an actual hydrogen gas thermometer. From the ideal gas, however, he may imagine the energy to be successively subtracted until the kinetic energy of the molecules is reduced to zero and the pressure which they are capable of exerting is also zero. Since each degree decrease in temperature, below zero on the centigrade scale, reduces the pressure by 1/273 of its value at zero centigrade it will only take 273 such decreases to arrive at an absolute zero of temperature. On this thermodynamic scale of temperature ordinary room temperature is obviously a little less than three hundred degrees.

In terms of absolute temperatures we may now express two important empirical laws of radiation.

The first of these is known as Wien's law. In any temperature radiation there is some frequency which has more radiation than is associated with any other frequency. This frequency becomes greater as the temperature is made higher; and it is directly pro-

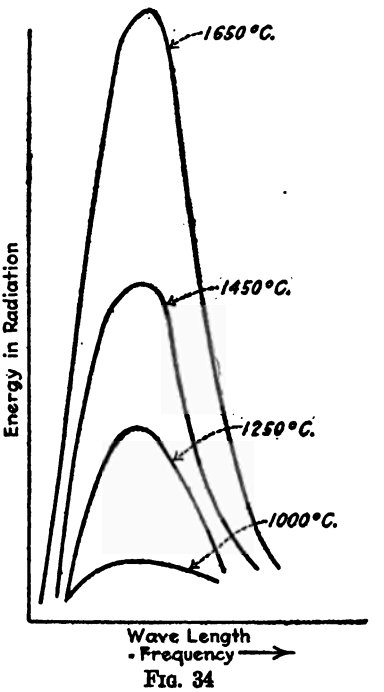


FIG. 34

Curves showing relation of intensity of radiation and frequency of radiating source at different temperatures.

portional to the absolute temperature. There is thus a displacement of the frequency of maximum radiation toward the ultra-violet portion of the continuous spectrum as is shown graphically in the curves of Fig. 34.

The other law, due to Stefan and Boltzmann, states that the total radiation from a heated body varies as the fourth power of the absolute temperature; thus if the temperature is doubled the rate at which energy is emitted is increased sixteen times. It is also illustrated by the curves of Fig. 34.

We are now ready to consider the occasion for Planck's development of the quantum theory. Up to the beginning of this century, when he made his contribution, no adequate theory had been developed to explain, or to picture, the experimental relations. These had been observed by careful experiments on enclosures the radiation from which was measured through a small peephole by delicate devices sensitive to heat.

There was, however, no theory on the basis of which formulæ could be logically developed which contained the relations of actual experiment. Planck solved the difficulty by reasoning the steps of which have never met with general approval but the conclusions of which are firmly established in the science of today.

The chief difficulty in the way of the existing theories concerned the manner in which a radiating body shares energy with its ethereal surroundings or absorbs it from them. It was commonly assumed that energy must be, or rather ought to be—for the condition was contrary to fact—interchanged in a continuous manner. A radiating surface was recognized as composed of a number of oscillators, but these were supposed to absorb or emit continuously, that is, in truly infinitesimal successive amounts.

from or to the ether. For such assumptions there was a recognized basis in theories of mechanics and electrodynamics. Of this a mechanical illustration may be quoted from Jeans.

Suppose we construct a vibrating system by connecting a number of corks together by elastic bands. Imagine a complicated system, if you will, with a large number of cross connections between various corks. Now disturb this by pulling some of the corks from their equilibrium positions and then allow the natural oscillations to occur. Let this system with its several different oscillations be placed on water. The corks simulate a vibrating system. The water, with its almost infinite number of tiny molecules, and hence infinite possibilities for forms of vibration, simulates the ether. We know what happens. Equilibrium between these two systems is impossible. The energy of the corks is all absorbed by the water. It goes into vibrations far more rapid than those of the corks, for it goes to increase the motions of the invisible molecules of the water.

If the ether were like this in behaviour all the energy of the bodies in a temperature enclosure would be abstracted by it. And the energy in the ether would be distributed mostly in the vibrations of highest frequency instead of having a distribution with a definite maximum as is shown in Fig. 34.

In effect Planck's solution of the difficulty consisted in postulating a condition which would fit the observed phenomenon.

To an economist or an actuary each experimental curve of Fig. 34 looks something like a so-called

probability curve, such a curve, for example, as one would plot if the vertical distances represented numbers of men and the horizontal distances represented corresponding lengths of life. If the various oscillators in the radiating body differ in their abilities to absorb or emit radiant energy, each being capable of only a definite amount, then the frequency of maximum radiation should depend upon the characteristics of these oscillators just as the maximum in a plotted curve of mortality statistics depends upon the characteristics of the class for which it is constructed. To a very large extent, as we shall see, Planck's theory constituted a theory of probability for electrical oscillators.

As you remember, he assumed that an oscillator could handle only a quantum of energy; and by quantum he meant an amount proportional to the frequency of vibration, the amount $hn$. Oscillators of low frequency, even if relatively numerous, will handle but a small portion of the total energy and contribute but little because the amount which each individual oscillator may handle is small. On the other hand, oscillators of large frequency will respond only if there is available a relatively large amount of energy since their quanta are greater. To function, however, the higher frequency oscillator must receive its quantum all at once; it cannot make it up from several successive smaller quanta. Since large quanta will probably occur only infrequently, this requirement means that there will be little total energy associated with the oscillators of high frequency. The maximum radiation, therefore, will occur in the

middle range of frequencies, as the experimental results indicate.

Upon the assumption of quanta Planck's relations are calculable under the ordinary laws of probability as was shown by Jeans some time later. For purposes of following the latter's method one limits his consideration to a narrow region of frequencies. The quantum will be essentially the same for all the frequencies within this narrow band. It is then possible to calculate the probability that any given oscillator of this frequency will have zero energy or the energy of one quantum or that of two, and so on. Summing up the energy which a large number of similar oscillators would probably have at this frequency, Jeans obtains the basic expression of Planck, namely, an expression for the probable average energy of an oscillator at any desired frequency.

It was Einstein, as a discrete, or indiscreet, electron remarked between chapters, who applied this relationship with considerable success to the problem of the specific heat of solids.

Different substances, but equal quantities by weight, are found to require different additions of heat, that is energy, to produce equal increases in temperature. The amount is specific to each substance, and hence, the term "specific heat" is applied to the amount of heat required to change by one degree the temperature of unit mass of a given substance. The common unit for expressing this magnitude is the calorie which represents approximately the amount of energy necessary to raise one gram of

water one degree Centigrade, and exactly, that required for the degree increase in temperature between 15 and 16 degrees Centigrade.

Temperature, of course, is a numerical answer to the question "how hot." As has been implied above, it measures the difference in hotness of substances the molecules of which differ on the average in the kinetic energy which is associated with their haphazard motions. If body "A" is hotter than body "B," the molecules of "A" have, on the average, more kinetic energy than those of "B". It is for this reason that a hot and a cold body when placed in contact come ultimately to a common temperature. By molecular collisions at the contiguous boundaries a portion of the energy of "A" is imparted to "B" until finally the molecules of both substances have the same average value of kinetic energy.

Because of differences in molecular structure one may predict at once that different substances will have different specific heats. A fairer basis of comparison, however, than amounts of heat for equal masses would be the amount required for equal numbers of molecules. Molecules of similar structure should require equal amounts of energy for equal changes in temperature, that is, they should have equal "molecular heats." Thus we should expect monatomic molecules to be alike in this respect.

In a monatomic structure the mass is almost entirely concentrated in the nucleus, which is the center about which any molecular rotation must occur. From the familiar example of flywheels, we know, however, that if a rotating body is to have associated

with it large amounts of energy, the mass must be separated from the axis of rotation by a large distance. Because monatomic molecules are not constructed on the plan of flywheels, for the planetary electrons are negligible in mass as compared to the nucleus, they have no appreciable energy of rotation. When heat is added to monatomic gases it all goes to increase the kinetic energy of translation of the molecules.

A diatomic molecule, however, would be expected to acquire and to store energy in a rotation or spinning of its figure-eight-shaped structure and particularly in a vibration of the component atoms with respect to each other. In the haphazard motion of such molecules when collision occurs, the atomic partners may be set spinning, or they may momentarily be crowded together, and thus vibrations may be set up within the molecular system itself. It appears evident that collisions will lead to such transfers of energy, and hence that some of the specific heat of diatomic substances will represent spinning and vibratory motions, in addition to the haphazard translations of the individual molecules.

The molecular specific heat of a substance should, therefore, depend upon the molecular structure, being greater for structures which have greater variety in possible types of motion—more degrees of freedom, as it is technically said. There is nothing, however, to indicate that the molecular specific heat should be different at different temperatures. We should expect that it would require the same fraction of a calorie to change a substance from 100 to 101

degrees as from 200 to 201 degrees. Of course, if a change in molecular state occurs as, for example, from liquid to vapor, the number of degrees of freedom may be changed and we may be dealing in effect with a different substance. As long, however, as there is no change of state, it would appear that the specific heat of any substance should be constant without regard to temperature.

For monatomic gases it is; also for metals in a vapor state; but for all other substances the specific heats are found to be markedly decreased as the temperatures at which they are measured are lowered. Here again no adequate theory had been presented prior to the application of the quantum hypothesis. The theory is still too incomplete to account for anywhere near all experimental facts, but the successes of the quantum hypothesis are sufficient to indicate that the final solution must involve its use.

Planck had derived an expression for the probable average energy, involving a large number of similar oscillators. This Einstein applied to the study of the specific heats of solids. The formula is too complicated for complete discussion, and it must suffice to say that it involves the absolute temperature of the substance. A mathematical operation was then required to find the rate at which this energy changed with temperature, that is to find the specific heat, which is the change in energy content of a body per degree of temperature. The expression so obtained was in form to permit the calculation of the specific heat of solid substances at any desired temperature if the frequency of the oscillators was known.

Several methods were then devised by Einstein and others for obtaining this frequency experimentally. Of these, only one will be discussed. This depends upon a number of principles which have already been mentioned. In the derivation of the formula for specific heat it had already been assumed, for simplicity, that all the oscillators of a homogeneous body were essentially alike. It remained to excite them in such a way that their characteristic or natural oscillations could be detected and their

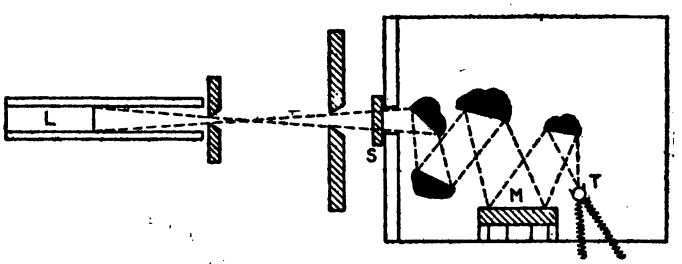


FIG. 35

Cross-section of apparatus for studying residual rays. Radiation from a source *T* is successively reflected from bodies of the same substance. The residual rays are analyzed by the spectrometer, diagrammatically indicated at *L*.

frequency measured. You will remember that reflection is really re-radiation. Any reflected radiation must then include most prominently those radiations which are of the same frequency as the oscillators would themselves naturally emit. The phenomenon is one of resonance, so-called—that is the phenomenon of greatest response when the appeal strikes the proper personal note.

If, therefore, a substance is illuminated by a continuous spectrum of radiation, such as would arise

from a black body which is emitting temperature radiation, the reflected radiation will contain more intensely the frequencies natural to the oscillators of the body. Now let this reflected radiation fall on another body of the same substance as the first. The general scheme is illustrated in Fig. 35, where the progress of the beam of radiation is indicated by the dotted lines. (A mirror, *M*, is interposed at one point to deflect the beam.) At the second reflecting surface there is a further selection of the natural frequencies, and a further discrimination against all others. By successive reflections there are thus obtained so-called "residual rays," which are those natural to the oscillators under examination.

When the natural frequency is known the calculation of specific heat by Einstein's method may be completed. For certain substances his formula was found to give results wonderfully in accord with the experimental findings. For other substances there was an unsatisfactory lack of agreement. Nevertheless, the formula agreed in such cases with the general trend of the relations between specific heat and temperature. It indicated a certain correctness of the general method of approach which other investigators have been rapidly extending. Thus inquiry in another field of physical science was stimulated and is being advanced by the fruitful hypothesis that energy is transferred in discrete bundles, the magnitudes of which are dependent only on the frequencies of the atomic and electronic oscillators which are concerned.

# CHAPTER XIV

## ENERGY AND ITS AVAILABILITY

In the earlier chapters of this book the orderly structure of matter was emphasized. In the later chapters some evidence was presented which favors a concept of "atomicity" for energy. Throughout, it is to be hoped that the text has conveyed an idea of the inherent structural order of nature. Now we must distinguish between order in structure and order in process. The processes of nature are orderly only in the sense that they constitute phases of an inevitable sequence of events. They may and indeed always do result in a certain disorder which we shall now consider. Of chaotic conditions we have had some intimations from the motions of molecules, particularly those of gaseous substances, and from the electrical elements which are responsible for continuous spectra.

The orderly processes of nature whereby disorder results have been formulated in a law commonly known as the second law of thermodynamics. It would be preferable to speak of a first and second law of energy rather than of thermodynamics, but they retain the titles, descriptive of their evolution, for both arose at a time when the relation between heat and energy was inadequately conceived. Both laws

express relations which have been grasped more or less intuitively, particularly the second law.

The first law states an equivalence between work (energy) and heat; and in mathematical symbols it contains an empirical constant for converting units of heat into units of energy. Prior to the statement of this law heat and mechanical work had seemed unrelated phenomena and different units had been adopted for the two magnitudes. Of these the calorie has already been defined; the other unit is the erg. Whenever, under experimental conditions, energy, associated with molar bodies, disappeared there was found a definite increase in heat which bore the proper numerical relationship to the amount of energy.

For many years, however, it has been recognized that heat is merely a descriptive term for the kinetic energy of molecular bodies. Today we conceive of energy as associated with all electrons and protons, with their configurations and their motions; and the first law becomes our statement of belief in the conservation or indestructibility of the entity energy.

The second law, which followed the work of Sadí Carnot about 1824, has also outgrown its earlier narrower application to heat engines and become a general law of energy. At various times it has received many expressions, of which the most serviceable are formulated in symbols and involve a concept known as entropy. To this we shall return in a moment.

In so far as the second law is a matter of experience it records the impression that there are certain

natural processes. Water flows down hill; electricity moves from points of higher to points of lower potential; by radiation, and by actual molecular impacts if possible, a net amount of energy is transferred from a hot to a cold body; impacts of molar bodies and all phenomena of friction result in transfers of energy to molecules. In fact, all natural processes, directly or ultimately, result in greater kinetic energy on the part of molecules. All mechanical operations involve friction and hence all contribute to increase the kinetic energy of molecular and submolecular systems. Similarly, the conduction of electricity and many [1] chemical reactions result in greater activity on the part of the tiny grains of our physical universe.

Sometimes the second law is stated by saying that although work (the expenditure of energy in connection with molar bodies) may always be converted into a definite equivalent of heat the reverse transformation is always incomplete. This was the earliest expression of the law and it was reached by a consideration of heat engines. Even if there were no friction whatever, a heat engine could never be 100 per cent efficient unless its lowest temperature was zero on the absolute scale of temperature. The proposition was originally proved by Carnot, who dealt theoretically with an ideal engine and found that the efficiency depended upon the ratio of the lowest temperature, say that of the atmosphere, to the highest temperature, say that of the boiler. The efficiency

[1] When we consider the surroundings as well as the reacting substances all reactions result in increases of entropy.

is always less than 100 per cent by the number of per cent represented by this ratio. Since temperatures are measured from the absolute zero it is evident that all actual conversions of heat into work are remarkably inefficient. Of the mechanical energy derived from heat energy there is always a certain amount which is expended in friction, so that the actual efficiency is even less than the "thermodynamic efficiency" which has just been explained.

Energy once converted into heat and embodied in molecular motions can never be completely recovered. Strictly speaking, therefore, all natural processes are irreversible because things can never be as they were. The fundamental cause of this so-called "thermodynamic irreversibility" is to be found in the characteristics of molecular systems.

Any material systems which we may use in experimental investigations involve billions and billions of molecules. With these we can only deal statistically treating of average effects. Because of their large number, however, the desired average effects may be studied by the laws and methods of probability, the mathematical science of chance.

In this field Maxwell made one of his many contributions to science. He determined the distribution of velocities, among the molecules of a gas, which would satisfy the experimentally observed condition that the pressure on the walls of a retaining vessel is constant when the temperature is constant. He found that no matter how collisions occurred there would be a definite average velocity (perpendicular to the surface of the container) and

that the proportion of the total number of molecules which had any particular velocity, either greater or less than the average, was definite and calculable. If a plot is made, showing the percentage of molecules striking the container and their corresponding velocities, the result is the form of probability curve shown in Fig. 36.

We have already met one application of the theory of probability in the development of an expression for the average energy of a large number of oscillators, each restricted according to the quantum hypothesis.

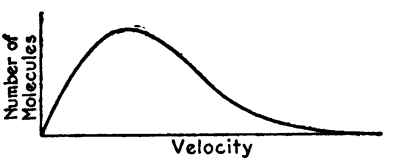


FIG. 36

Diagrammatic representation of Maxwell's distribution of molecular velocities.

We shall now sketch briefly an application of the method of probabilities by which Boltzmann arrived at a concept of entropy, the characteristic magnitude in terms of which the second law is most satisfactorily expressed. Imagine looking across two parallel tennis courts. The players are warming up for two sets of doubles and each member of a team is volleying with an opponent so that four balls are constantly in the air. We shall distinguish between the balls by the letters a, b, c, and d.

The distribution of the balls with reference to the line of the nets changes from instant to instant. At one moment all four may be on the east side, and a

moment later three on that side and one on the west. There are obviously five possible distributions, namely: all east, all west, three east and one west, or vice versa, and two on each side of the net.

For any distribution there is one or more "complexions," as they are called. Thus the distribution of three east and one west might be the result and would correspond to any one of four complexions, for there are four different ways in which we may have three balls on one side and one on the other. If we tabulate the various possible complexions we have the result given below:

| Distribution | | Complexion | |
|---|---|---|---|
| East | West | East | West |
| 4 | 0 | abcd | |
| 3 | 1 | abc | d |
| | | abd | c |
| | | acd | b |
| | | bcd | a |
| 2 | 2 | ab | cd |
| | | ac | bd |
| | | ad | bc |
| | | bc | ad |
| | | bd | ac |
| | | cd | ab |
| 1 | 3 | a | bcd |
| | | b | acd |
| | | c | abd |
| | | d | abc |
| 0 | 4 | | abcd |

The distribution of two balls on either side of the net is the most probable distribution. Out of six-

teen possible complexions this distribution contains six, and that with the next largest number contains four. For purposes of later analogy we also note that this distribution of two and two represents a sort of an equilibrium condition. We might also note that from the standpoint of an attendant, who is accustomed to seeing balls neatly packed in dozens, the distribution is not that of order.

Now forget the players, letting the balls represent molecules of a gas and let their number be enormously increased. There will still be a distribution which will contain the maximum number of complexions and this will be the most probable distribution. It will also be the most probable state for the gas, the final "equilibrium state" toward which systems of gas molecules inevitably tend. It will be the state with the largest number of complexions and the greatest number of ways in which the gas molecules may be associated, the state of greatest disorder.

As Boltzmann defined it, "thermodynamic probability" is a number which expresses how much more probable a given state is than some "standard" or perfectly ordered state in which the substance occupies the same volume and has the same energy. For example, from the preceding table we see that the probability of the most "mixed-up" state is six times that of the state where all the balls are on one side of the net. The mixed-up state is most probable. There is always a natural trend toward the greatest disorder, toward the state of final equilibrium.

When four balls are on one side of the net there is

greater energy associated with this side than with the other. Hence, if we were dealing with molecules we would expect to obtain some of this energy by allowing them to pursue their natural haphazard motions and by their impacts to drive before them a molar body like the piston of an engine. Haphazard motions will carry the balls across the net and they can do mechanical work, as, for example, upon a racquet held in their way. In the equilibrium state, however, no mechanical work can be recovered, for on the average a racquet held over the net would receive as many and as hard impacts from one side as from the other. We now see that we cannot utilize or obtain from a gas, in the state analogous to four balls on one side, all the energy which its molecules appear to be able to expend, since the natural process upon which we rely proceeds only to a final equilibrium state corresponding to that of two balls on either side of the net.

Unfortunately for the purposes of easy exposition, thermodynamic probability and entropy are not synonymous. There is, however, a definite relation between them. If one increases the other also increases but not in direct proportion. With this understanding we may proceed to use the term entropy in place of thermodynamic probability.

All systems tend to a final state of maximum entropy, that is a condition of greatest molecular disorder from which no mechanical work may be derived. Not only no mechanical work but also no chemical or electrical changes can be brought about by such a system of itself in such a manner as to per-

mit energy to be derived from these changes. The equilibrium condition is a "run-down condition" which offers no hope to human beings who would control nature's store of energy. Although energy is still associated with the system its availability has disappeared.

Human beings need never be concerned with the conservation of energy since that is apparently inherent in the entity itself. Their concern is with its availability. When energy transformations occur naturally, and in final analysis all transformations so occur, there is a reduction in availability, or as the scientist says, an increase in entropy. There is no known or anticipated scientific process, despite all the discoveries of radioactive substances, whereby this inevitable and natural increase in entropy may be avoided. It does seem unnecessary, however, that man should accelerate the irreversible transformations of nature. This he does whenever he fails to take from a natural process, as, for example, from the combustion of coal, the full amount of useful energy which is his equity in accordance with the second law of thermodynamics.

The final end of any conservative system, one which does not have energy communications with its neighbors, is not stagnation but disorder. Orderly systems may have no more energy than disorderly systems but their energy is partly available. Inevitably any orderly system tends to a state of maximum disorder. In the process of attaining this state its own entropy is increased. Only a certain amount of its energy is available and the expenditure of this

margin is man's concern. It may be expended with foresight, as when a waterfall is utilized to make chemical compounds in which available energy is stored for later release, for example, in nitrogenous fertilizers. It may be expended without foresight in the innumerable ways which history records. Every fire or explosion, every inefficient process, represents an increase in the world's entropy—the sum total of its disorder.

# APPENDIX

## THE MAGNITUDES OF ELECTRONS AND QUANTA

To a considerable extent the exposition of the previous text has been unrelated to our daily experiences. It has dealt with minute protons and electrons, with quanta of energy, and with granular structures so fine that they are only to be inferred and never to be seen. In this Appendix it is now proposed to assemble some numerical expressions whereby the tiny magnitudes involved in the modern science of electrons and quanta may be related to the grosser magnitudes with which we are familiar.

In terms of the fundamental scientific units, namely, the centimeter (1 cm.=0.394 inch), the gram (1 g.=0.0353 ounce), and the second, the sizes and masses of the electrical elements are extremely small and their number in any sensible volume extremely large. Where extremes are to be met, numerical expression is most conveniently accomplished by a slight modification of our common decimal system.

Consider first the expression of numbers greater than ten. Ten is one times ten; a hundred is one times ten times ten; and one thousand is one times the successive product of three tens; and so on as in

the table below. The number of successive products of ten is represented by an exponent of the proper value as shown.

| | | |
|---|---|---|
| $10 = 1 \times 10$ | | $= 1 \times 10^{1}$ |
| $100 = 1 \times 10 \times 10$ | | $= 1 \times 10^{2}$ |
| $1000 = 1 \times 10 \times 10 \times 10$ | | $= 1 \times 10^{3}$ |
| $10000 = 1 \times 10 \times 10 \times 10 \times 10$ | | $= 1 \times 10^{4}$ |
| one million = | | $= 1 \times 10^{6}$ |
| one billion = | | $= 1 \times 10^{9}$ |
| one million million = | | $= 1 \times 10^{12}$ |
| one billion billion = | | $= 1 \times 10^{18}$ |

On the same basis, any number like 606 is 6.06 times a hundred or as illustrated below:

$$606 = 6.06 \times 10^{2}$$
$$6060 = 6.06 \times 10^{3}$$
$$60600 = 6.06 \times 10^{4}$$

When later we find that the number of molecules in two grams of hydrogen gas is $6.06 \times 10^{23}$ we shall be able to convert this expression into 606 thousand billion billion, and thus, perhaps, get some appreciation of an enormous number.

For numbers smaller than unity the system is equally simple. We write 1/10 as $10^{-1}$; and 1/100 as $1/10^{2}$ and then as $1 \times 10^{-2}$, as in the following table:

| | | |
|---|---|---|
| 0.1 | $= 1 \times 1/10$ | $= 1 \times 10^{-1}$ |
| 0.01 | $= 1 \times 1/100$ | $= 1 \times 10^{-2}$ |
| 0.001 | $= 1 \times 1/10^{3}$ | $= 1 \times 10^{-3}$ |
| one millionth = | | $= 1 \times 10^{-6}$ |
| one billionth = | | $= 1 \times 10^{-9}$ |
| one billionth of a billionth = | | $= 1 \times 10^{-18}$ |

The use of these negative powers of ten is illustrated below:

$$0.254 = 2.54 \times 1/10 = 2.54 \times 10^{-1}$$
$$0.0254 = 2.54 \times 10^{-2}$$
$$0.00254 = 2.54 \times 10^{-3}$$
$$0.000,002,54 = 2.54 \times 10^{-6}$$

In addition to the convenience and brevity which this system offers it serves to indicate most quickly the order of magnitude of a number and its significant figures. Consider for example the value of Avogadro's constant, that is the number of molecules in one "mole" of any substance. [1]

The most exact value for this constant is $6.062 \times 10^{23}$, as found by Millikan.

From the second portion of this expression we recognize at once that the constant is of the order of hundreds of thousands of a billion billions. The first portion of the number contains the significant figures. If Millikan's determination had been less precise he might have found $6.06 \times 10^{23}$, or with still less accuracy $6.0 \times 10^{23}$. In the latter case he would not have written the number as $6.000 \times 10^{23}$ for that would have implied the same precision as does his actual value, that is a precision to the fourth significant figure.

By the number of significant figures an experimenter indicates the correctness of his results so far as concerns the precision with which he has made his measurements. He does not, of course, mean that

[1] A mole is a number of grams equal to the molecular weight of the substance; thus in the case of hydrogen, $H_2$, a mole is two grams, but in that of oxygen, $O_2$, it is 32 grams. Without regard to substance all moles will contain the same number of molecules.

there may not be present in his determination sources of error, inherent in the experimental conditions, which may have rendered his results wrong even in order of magnitude. By proper attention to significant figures throughout any necessary calculations he arrives at a final result each figure of which is really significant and not merely a result of an arithmetical process.

Taking a simple example, suppose he wishes to compute the circumference of a circle the diameter of which he has measured as 10.0 cm. He multiplies this diameter by $\pi$, but he uses for $\pi$, 3.14 and not 3.14156 or some still more accurate value. By his expression of the diameter as 10.0 cm. he means in substance that he has measured it with a centimeter scale which is divided into tenths of a centimeter, and that he does not know its value closer than a tenth of a centimeter. To write the circumference as 31.4156 cm. would imply a greater accuracy than he has either right or desire to imply.

When, therefore, we consider Millikan's value for Avogadro's constant we interpret it to mean that he has determined the number of molecules in a mole to the fourth significant figure. His value, then is in doubt by approximately $0.001 \times 10^{23}$ or a mere matter of a hundred or so billion billion molecules. He is right, however, to within about one-hundredth of one per cent. A more exact knowledge than this would probably avail us but little since there are few physical conditions where we may detect a percentage difference as small as this, and few physical con-

stants which are expressible by more than four significant figures.

We are now in a position to express numerically some important physical magnitudes. We shall not, however, go into any detail as to how they have been determined. Further, we shall allow the numerical values to create their own impressions instead of adopting conventional expedients to heighten them. For example, one might count the average number of letters on a page of the encyclopædia, divide this number into Avogadro's constant and find the number of pages which would be required to contain a number of letters equivalent to this number of molecules, and then calculate the number of billions of complete sets [1] and so convey an impression. With more tediousness he could take the volume of atmospheric gas inspirated by an average man in a single breath and by using Avogadro's constant express the number of molecules for this familiar case in terms of volumes of the encyclopædia. Arithmetical dexterity and interest will produce strange results by such a method, and the arithmetic is facilitated by the use of powers of ten.

*Sizes*: Known distances in the physical universe extend from $10^{24}$ cm., representing the distance from the earth to the further nebulæ, to $10^{-13}$, representing the order of magnitude of the diameter of an atomic nucleus. With the microscope one can observe distances in ordinary light of the order of $10^{-5}$ cm., and can detect illuminated specks of somewhat smaller

[1] The advertisements say $4.4 \times 10^6$ words per set. Hence, allowing six letters to the word, almost a billion billion sets.

dimensions. The diameter of a molecule of oxygen is $2.99\times10^{-8}$ cm. For hydrogen the diameter is less, being $2.17\times10^{-8}$ cm. The best indications of the diameter of an electron give $2\times10^{-13}$ cm.

*Masses*: The mass of a hydrogen molecule is $3.33\times10^{-24}$ g., and the mass of any other molecule is larger in proportion to its molecular weight, thus that of the oxygen molecule is $52.8\times10^{-24}$ g. The mass of the atom of hydrogen is half that of its molecule and this is also the mass of the proton. The mass of an electron is only about 1/1845 of the proton and is thus $9.01\times10^{-28}$ g.

*Velocities*: The greatest velocity in the physical universe is that of light or of other forms of radiant energy. Light quanta apparently travel $2.999\times10^{10}$ cm. per second. Beta particles have been measured with velocities as high as 9/10 of this. Alpha particles, with their greater mass, are ejected with smaller velocities in the order of 1/10 the velocity of light.

In a volume of gas under practically atmospheric conditions of pressure and temperature (so-called standard conditions) molecules travel with velocities which are dependent upon their masses. Hydrogen molecules travel fastest, about a mile a second or $1.69\times10^{5}$ cm. per second. Oxygen molecules with sixteen times the mass travel one-quarter as fast as hydrogen molecules, that is $4.2\times10^{4}$ cm. per second.

*Free Path of Gas Molecules*: Under these standard conditions the atoms of a volume of hydrogen would travel on the average about $1.76\times10^{-5}$ cm. between successive collisions. On the average, there-

fore, a hydrogen atom would make ten billion collisions per second. If the gas is less dense, for example, if the container has been exhausted until the pressure is $2.64\times10^{-10}$ of the normal atmospheric pressure, the number of molecules per c.c. has been similarly reduced and the mean free path is increased by $3.8\times10^{9}$ times. For oxygen, for example, the mean free path under atmospheric conditions is $9.4\times10^{-4}$ cm. and under the above conditions of rarefaction $3.54\times10^{4}$ cm.

The velocity has not been altered by the reduction in pressure for the temperature has been assumed unchanged, and hence the kinetic energy is not altered. The molecule will now make only about one collision a second. Such extreme conditions of rarefaction are producible today by vacuum pumps which employ molecules to bombard other molecules and thus drive them from the desired enclosure. When the bombarding molecules have done their work they are removed by condensing them into drops of liquid.

*Avagadro's Constant*: A mole of any gas occupies a volume of $2.241\times10^{4}$ c.c., that is, about 22 liters (about 0.79 cubic foot) under standard conditions of temperature and pressure. In this mole there are, as has been said, $6.062\times10^{23}$ molecules. Per cubic centimeter, therefore, there are about $2.705\times10^{19}$ molecules. Under the conditions of rarefaction which were mentioned above as attainable by the modern mercury vapor vacuum pump the number per c.c. is reduced to about $7\times10^{9}$, so that the nearest we can come to a perfect vacuum is a mere

matter of several billion molecules in each cubic centimeter.

*Energy Units*: The unit of energy is the erg. It represents twice the kinetic energy which is associated with a mass of one gram which is moving at the rate of one centimeter a second. It represents roughly one-thousandth of the work required to raise a gram vertically one centimeter. It is too small a unit for convenience in practical mechanics. For example, in lifting an ounce vertically a distance of 1-inch one does $7.07 \times 10^4$ ergs of work. The familiar unit of energy, known as the foot-pound, is equivalent to $1.35 \times 10^7$ ergs. The joule which is used in electrical engineering is $10^7$ ergs. The calorie which is the convenient unit for measuring energy which appears as heat is equivalent to $4.19 \times 10^7$ ergs.

*Quanta*: Although the erg is too small for many practical purposes it is large compared to many of the amounts of energy with which the scientist is concerned. This is particularly so in the case of quanta. Planck's constant is $6.56 \times 10^{-27}$ and the number of ergs representing a quantum at any given frequency is the product of this constant, $h$, and the frequency $n$. For example, about the highest frequency of visible light is $7.5 \times 10^{14}$ vibrations per second, so that the corresponding quantum is $5.0 \times 10^{-12}$ erg. The frequency at which a heated body radiates the maximum amount of energy is about $1.5 \times 10^{14}$, which is in the infra-red region. The corresponding quantum is only $9.9 \times 10^{-13}$ erg.

Gamma rays have the highest known frequencies, about $10^{20}$ vibrations per second. In this case the

quantum has its maximum known value of about $6 \times 10^{-7}$ erg.

*Kinetic Energy of a Gas Molecule:* The kinetic energy which, on the average, is associated with each molecule of a gas under standard conditions of pressure and temperature (0°C.) is $5.62 \times 10^{-14}$ erg, and for every degree increase in temperature the kinetic energy of translation is increased by $2.06 \times 10^{-16}$ erg.

*Electrical Units:* For measuring electrical phenomena three systems of units are used, but we shall restrict ourselves to the so-called practical units known to electricians and the consumers of electrical energy.

*The Electron:* The practical unit of quantity of electricity is the coulomb. It represents the amount of electricity which would be transferred in a silver-plating solution of silver nitrate every time that 0.001118 gram of silver is deposited on the cathode. If a coulomb is passed through an electrolyte under conditions where hydrogen is liberated the mass of hydrogen gas is $1.038 \times 10^{-5}$ gram. To liberate a gram of hydrogen requires the passage of 96,500 coulombs. In terms of the coulomb the charge of an electron (or of a proton) is $1.591 \times 10^{-19}$ coulomb.

*Current:* When there is a transfer of electricity through any conductor at the rate of one coulomb per second a current of one ampere is said to be flowing. It is thus evident that a current of one ampere represents a flow across each and every cross-section of the conductor of $6.3 \times 10^{18}$ electrons each second.

*Electrical Potential:* When a coulomb of elec-

tricity is transferred between two points by an expenditure of one joule of energy ($10^7$ ergs) the points are said to differ in electrical potential by one volt. The lighting circuit of a house or office usually operates at a voltage of 115.

*Power*: By multiplying the voltage across and the current through any piece of electrical apparatus we find the number of joules per second which are being expended in the apparatus. For joules per second, however, there is used a single word, namely, watts. When energy is being expended at the rate of one joule per second the power in the circuit is one watt. An ordinary house light, rated as 40 watts, takes a current of 40/115 ampere or a little more than a third of an ampere, and represents a flow of electrons at the rate of about $2.\times10^{18}$ a second.

*Ionization Potential*: The kinetic energy which an electron acquires in free passage between two points differing in potential by one volt is about $1.59 \times10^{-11}$ erg. Ionization potentials are of the order of 10 volts so that it requires about $1.6\times10^{-10}$ erg to knock an electron free from an atomic structure. The ionization potential differs with the type of atom and some atoms require two or three times as much energy in the impact as do others. To ionize by removing two electrons requires more energy but the amount is still absurdly small compared to any of the energy expenditures of our daily lives.

*X rays*: In an X-ray tube the electrons freed at the heated cathode are pulled across the intervening

space to the target under voltages of the order of 150,000. As a result each electron delivers to the target an energy of about $2.4\times10^{-6}$ erg. This is about the highest value of energy which physicists have yet been able to impart to an electron.

*The Inconstancy of Mass*: Mass or inertia, as defined on page 40, depends upon energy and speed. Neglect for the moment the conventional units used in this Appendix and return to the simple units of the previous text. An electron moving with unit speed (1 cm. per sec.) has unit energy and under these conditions the electron has unit inertia. If it moves with twice the speed it has four times the energy; with three units of speed, nine units of energy; and so on, the energy of the moving electron being equal to the square of its speed *as long as this speed is small as compared to the velocity of light* ($3\times10^{10}$ cm. per second). Under these conditions the inertia or mass of the electron is constant and is measured by the ratio of the number of units of energy to the square of the number of units of speed.

Actual comparisons have been made of the energies of electrons at different speeds and it has been found that as higher speeds were attained the energy was increasing enormously faster than was the square of the velocity, that is, that the inertia of an electron is not constant but always greater for greater speeds, although the differences are imperceptible at speeds small as compared to light. For this reason the mass may be said to be inconstant. The same relation holds for molar bodies as well as

electronic if we accept, as we must, the so-called "special relativity theory." This subject, however, demands a whole book to itself, and it has received many such in recent days.

# GLOSSARY

ABSOLUTE ZERO
A temperature of 271.3° below zero on the Centigrade scale, equivalent to 456.3° below zero Fahrenheit.

ABSORPTION SPECTRUM
A spectrum showing by their absence what radiations a given substance fails to transmit.

ACIDS
Electrolytes for which one product of dissociation is a hydrogen ion.

ALPHA PARTICLES
The combination of four protons and two electrons which is expelled from the nucleus of a radioactive atom. An alpha particle is identical with the nucleus of a helium atom.

ALPHA RAYS
A stream of alpha particles.

AMPERE
A unit of electrical current. See Appendix.

AMPHOTERIC
A term applied to chemical elements which react either as electropositive or electronegative depending on the other reactants.

ANODE
The plate or other terminal in a conducting gas or liquid at which electrons or negative ions are collected. The positive electrode.

ANTI-CATHODE
The anode or target in an X-ray tube.

ATOM
An atomic system which is uncharged having equal numbers of protons and electrons.

ATOMIC NUMBER
A number equal to the number of positive charges

(protons) of a nucleus in excess of the number of negative charges (electrons).

ATOMIC SYSTEM
A nucleus and associated planetary electrons. It may be either a normal atom or an ion.

ATOMIC WEIGHT
The number representing, on a scale which assigns 16 to oxygen, the average mass of the atom of any chemical substance.

ATOM-MODEL
A theoretical configuration of the electrons in an atom which would account for its properties.

BASES
Electrolytes for which one dissociation product is a negative ion formed by an oxygen and a hydrogen atom.

BETA PARTICLE
An electron which is ejected by the nucleus of a radioactive atom.

BETA RAYS
A stream of beta particles.

CALORIE
A unit of energy used in discussing heat. *cf.* p. 178.

CARBOHYDRATE
A chemical compound of a particular type which contains carbon, hydrogen and oxygen. Of this type the sugars are examples.

CATHODE
A plate or other terminal in a conducting gas (or liquid) at which positive ions are collected or electrons are emitted. The negative electrode.

CATHODE RAYS
A stream of electrons proceeding outward from the cathode of a tube (of gas) which is conducting electricity.

CENTIMETER
Approximately 0.394 inch.

CHARGE
The excess of positive or negative electricity in a body.

CHEMICAL ELEMENT
A substance all of whose atomic systems have the same atomic number.

CONTACT ELECTROMOTIVE FORCE
The potential difference which is set up by the contact of two dissimilar substances, i. e., substances with different electronic structure.

CONTINUOUS SPECTRUM
A spectrum which includes all possible frequencies.

COULOMB
A unit of charge. *cf.* Appendix.

DISSOCIATION
A disruption of a molecular system which may or not, as the case may be, result in neutral systems. Electrolytes dissociate into charged systems, the ions.

DISINTEGRATION
A disruption of the nucleus of an atomic system.

DISINTEGRATION PRODUCT
The atomic system which results when alpha or beta particles are expelled from a nucleus.

ELECTRICAL ELEMENTS
The electron and the proton.

ELECTRODE
The metal plate which terminates the solid portion of an electrically conducting path, the other portion of which either is gaseous or liquid or is a vacuum.

ELECTROLYTE
A solution for which the solute partially dissociates into ions.

ELECTROMAGNET
A piece of magnetic material about which is wound a current-carrying loop of wire.

ELECTROMAGNETIC THEORY
The generally accepted theory of electricity and magnetism which was formulated by Maxwell.

ELECTROMETER
An instrument for measuring an electrical charge.

ELECTRON
The elementary corpuscule of negative electricity. It is complementary to the proton.

ELECTRONEGATIVE
A term applied to chemical elements whose atoms have a negative valence.

ELECTROPOSITIVE
The opposite of electronegative.

ELECTROSCOPE
An instrument for detecting an electrical charge.

ELECTROSTATIC
A term applied to an electrical charge which is fixed in position.

EMANATION
The name applied to the product formed by the expulsion of alpha particles from the nucleus of radium or thorium atoms. In this book radium emanation is called "niton."

EMISSION SPECTRUM
The spectrum of the radiation from a body.

ENERGY
The name applied to the motive power in the physical universe. One of the two fundamental entities of modern physics; the other is electricity.

ENTROPY
A numerical expression which increases as energy loses its availability.

ERG
A unit of energy. *cf.* Appendix.

FLUORESCENT
Giving rise to radiations of other frequencies than those which it absorbs.

FREQUENCY
Number of oscillations per second.

GAMMA RAYS
A radiation, similar in type to X-rays, which proceeds outward from some radioactive atoms when the substance is emitting beta rays.

GRAM
A unit of mass approximately equal to 0.0353 ounce.

GRATING
A series of equally spaced reflecting surfaces which serve to analyse radiations into their component frequencies.

INERTIA
A characteristic unwillingness to change in state of motion which all bodies display.

INFRA-RED
Of lower frequency than the visible radiation.

INTERFEROMETER
An instrument for measuring distances very accurately in terms of wave lengths of visible light. Used by Michelson to measure the international meter.

ION
An atomic or molecular system which is electrically charged by virtue of an inequality in the number of its protons and its electrons.

IONIZATION
A disruption of an atom or molecule into ions or into ions and electrons.

IONIZATION POTENTIAL
The amount of potential energy which must be converted into kinetic in order that an impact of the body with which the energy is associated shall ionize an atom or molecule.

ISOTOPE
A substance which occupies with another substance the same place in the periodic table of chemical elements. The two substances then have the same atomic number but different atomic masses.

JOULE
A unit of energy. *cf.* Appendix.

KINETIC ENERGY
Energy associated with electricity in motion.

LINE SPECTRUM
A discontinuous spectrum formed by radiation of only certain definite frequencies.

MASS
The amount of matter in a body; more strictly, a measure of its ability to acquire kinetic energy.

MOLE
A number of grams of a given substance equal to the sum of the atomic weights of all the atoms in a molecule of the substance.

MOLECULAR HEAT
The heat required per molecule (strictly per mole) to raise the temperature of a substance 1° centigrade.

MOLECULAR SYSTEM
A union formed by two or more atomic systems. It may be either a normal molecule or an ion.

MOLECULE
A molecular system which is uncharged, having equal numbers of protons and electrons.

NITON
Radium emanation. An inert gas of atomic number 86.

NUCLEUS
One or more protons associated with electrons in a compact group central to an atomic system.

OSCILLATOR
An atomic or electronic system the parts of which vibrate or oscillate.

PELLATE
Move apart except as restrained.

PERIODIC TABLE
The arrangement of the chemical elements, in ascending order of atomic numbers, in which elements of somewhat similar electronic structure, and hence chemical properties, appear periodically.

PHOSPHORESCENT
Emitting radiation as a result of radiation which is absorbed but after absorption has ceased.

PHOTO-ELECTRIC
Pertaining to the emission of electrons which occurs under the action of light.

PLANCK'S CONSTANT
The factor of proportionality by which the frequency of an electronic oscillator must be multiplied in order to express a quantum in ergs.

PLANETARY ELECTRONS
The electrons in an atom which are external to the nucleus.

POLYMERIZATION
The formation of aggregates of molecules which move about (in solution) as if they were single molecules.

POSITIVE RAYS
A stream of positive ions from a tube of conducting gas.

POTENTIAL DIFFERENCE
A measure of the potential energy which is available between two points.

POTENTIAL (ELECTRICAL)
The measure of the potential energy which is associated with a unit quantity of electricity.

POTENTIAL ENERGY
Energy which it is assumed, upon the basis of the conservation of energy, is associated with the configuration of electrical systems.

POTENTIAL GRADIENT
The rate at which the potential difference between two points changes as the position of one is varied.

PROTON
The elementary corpuscule of positive electricity. It is complementary to the electron.

QUANTUM
A variable amount of energy, directly proportional to the frequency of the radiation which is emitted by an electronic oscillator.

RADIATION
Energy, unassociated with matter, which is being transferred through space.

RADIOACTIVE
A term applied to substances the nuclei of whose atoms spontaneously disintegrate.

RADIUM
The most famous radioactive substance, discovered by the Curies in 1897.

RE-RADIATION
Radiation emitted by a body which is absorbing radiation from a distant source.

RESISTANCE (ELECTRICAL)
The unwillingness of a body to transmit electricity, which is measured by the ratio of an electrical potential (the cause) to a current (the effect).

RESONANCE POTENTIAL
The amount of potential energy which must be con-

verted into kinetic in order that an impact shall excite the characteristic radiation from an atom.

SALTS
Electrolytes which are neither acids nor bases.

SCINTILLATION
A discrete speck of light produced in a screen by the impact of a high speed ion, usually of an alpha particle.

SOLENOID
A tubular winding of wire formed by spiralling a wire as in Fig. 4.

SPECIFIC HEAT
Energy required to raise the temperature of unit mass of a substance one degree.

SPECTROMETER
An instrument for the quantitative analysis of radiation into its component frequencies.

SPECTROSCOPE
An instrument for the qualitative investigation of the component frequencies of a given radiation.

SPECTRUM
A broad band of radiation in which the several component radiations are arranged side by side in the order of their frequencies.

TEMPERATURE ENCLOSURE
A region surrounded by walls which are maintained at a constant temperature.

TEMPERATURE EQUILIBRIUM
The condition of a system the parts of which undergo no relative changes in temperature.

TEMPERATURE RADIATION
Radiation emitted as the result of the thermal agitation in a body.

THERMION
An electron emitted from a body as a result of thermal agitation.

THERMODYNAMIC EFFICIENCY
*cf.* p. 186.

THERMODYNAMIC PROBABILITY
*cf.* p. 190.

THERMODYNAMIC SCALE OF TEMPERATURE
A temperature scale starting from the absolute zero.

THRESHOLD FREQUENCY
The minimum frequency of radiation which will produce photo-electric effects.

TRACTATE
Move toward each other except as restrained.

ULTRA-VIOLET
Of higher frequency than visible radiation.

VALENCE
A numerical statement of the ability of atoms to combine, expressed in terms of the combining ability of hydrogen as unity, e.g., hydrogen, sodium, chlorine are monovalent; oxygen, sulphur and zinc are divalent; phosphorus and boron are trivalent and carbon and silicon are tetravalent.

VELOCITY
Rate of change of position, that is speed, measured in distance per unit of time.

VOLT
A unit of potential difference. *cf.* Appendix.

WATT
A unit of power, that is of the rate at which energy is expended. *cf.* Appendix.

WAVE LENGTH
The distance traversed by radiant energy in the period occupied by one complete oscillation of its source. Numerically equal to the velocity of light divided by the frequency.

X-RAYS
The radiation from the anode or target of a vacuum tube, when the anode is subjected to severe bombardment by a cathode stream.

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